Natural Philosophy for General Readers and Young People

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ARNOLD WILLIAM REINOLD

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GANOT'S

NATURAL PHILOSOPHY


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NATURAL PHILOSOPHY

FOR

GENERAL READERS AND YOUNG PEOPLE

TRANSLATED AND EDITED FROM

GANOT'S COURS ÉLÉMENTAIRE DE PHYSIQUE

(WITH THE AUTHOR'S SANCTION)

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TENTH EDITION, CAREFULLY REVISED

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PREFACE

TO

THE TENTH EDITION

THIS work is founded upon Ganot's *Cours élémentaire de Physique*, which has had a large circulation in France. The translation was made by the late Dr. E. Atkinson. It was not, however, a mere translation, but such additions and alterations were introduced as were thought fitted to render the book useful as a text-book of physics for the upper and middle classes of boys' and girls' schools, and as a familiar account of physical phenomena and laws for the general reader. Mathematical formulæ were as far as possible carefully avoided.

The first eight editions and part of the ninth were due to Dr. Atkinson. The present edition has been carefully revised, and a certain amount of new matter has been added.

A. W. REINOLD.

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OF

NATURAL PHILOSOPHY

BOOK I

GENERAL PROPERTIES OF MATTER, AND UNIVERSAL ATTRACTION

CHAPTER I

PRELIMINARY NOTIONS

1. **Definition of physics.**—The word *physics* is derived from the Greek φύσις, nature; for the ancients understood by the term physics the study of the whole of nature. They comprised within the domain of this science ***mechanics***, ***astronomy***, ***chemistry***, ***botany***, ***zoology***, ***medicine***, and even ***astrology*** and ***divination***, whether by the stars or by the observation of physiognomy.

The province of physics is now more restricted. Its object may be considered to be *the study of those phenomena which do not depend on changes in the composition of bodies*; for these belong to chemistry.

Thus, when water by cooling is changed into ice, and when this ice by being heated is again changed into water, the liquid is exactly the same as before: not merely are all its properties the same, but its volume is identical with what it originally was. The passage of water to the state of ice, and the return of the latter to the liquid state, are *physical phenomena*. In like manner, when a brittle object, one of porcelain or of glass, for instance, falls to the

ground and breaks, each piece retains exactly the same chemical composition. The fall of the vessel and its fracture are, then, physical phenomena.

On the other hand, when wood burns, its substance is completely modified. It consists of several different forms of matter, and is decomposed: one part of its elements passes into the atmosphere in the form of gas and vapour, while another is left as a residue consisting of ash and charcoal. In short, the substance we know as wood has disappeared, and is replaced by others which are entirely different. The combustion of wood is accordingly a *chemical phenomenon.*

2. **Matter, mass, density.**—We understand by the term *matter* whatever can affect one or more of our senses : that is to say, anything the existence of which can be recognised by the sight, touch, taste, smell, or hearing.

The *mass* of a body is a quality inherent in each body and independent of its state of rest or of motion, as well as of its position in reference to other bodies ; the mass results from *the quantity of matter* contained in the body. Different substances may contain very different quantities of matter in the same volume. It will subsequently be shown, for instance, that, for equal volumes, lead contains nearly eleven times as much matter as water, and gold nineteen times as much. This is expressed by saying that lead and gold are respectively eleven and nineteen times as *dense* as water. When one body has, for the same volume, twice or thrice the mass of another, it is said to be twice or thrice as dense ; and the *density* of one substance in reference to another is the number which expresses how much matter the first body contains as compared with the second.

By various modes of investigation it has been ascertained that all the various forms of matter with which we are acquainted may be resolved into about seventy different kinds, which are called *simple substances* or *elements*, to express that each only contains one kind of matter. Many of these are very rare, and are found in very minute quantities : others are more widely diffused, and have important uses but are not abundant ; and the great mass of our globe is made up of about fourteen—the *non-metallic bodies*, or *metalloids*, oxygen, hydrogen, nitrogen, silicon, carbon, sulphur, phosphorus, and chlorine ; and the *metals* aluminium, potassium, sodium, calcium, magnesium, and iron.

Very few of these elements occur in nature in the free state ; by

far the greater number of the substances we know are ***compound*:** that is, are formed by the union of two, three, or four of these elements. Thus, water consists of hydrogen and oxygen ; sand, of silicon and oxygen ; salt, of chlorine and sodium ; wood, of carbon, oxygen, and hydrogen ; marble, of carbon, oxygen, and calcium ; muscular tissue, of carbon, hydrogen, oxygen, and nitrogen. The number of substances containing more than four elements is very small.

The force in virtue of which different substances unite to form compounds, and which opposes the separation of compounds into their elements, is called the force of ***chemical attraction*** or ***affinity***.

This force is exerted between bodies with different degrees of intensity. Thus, if we mix finely powdered vermilion, a compound of sulphur and mercury, with iron in a fine state of division, and heat the mixture, we shall find that the iron combines with the sulphur, forming a new compound, the sulphide *of* iron or iron sulphide, while the mercury is set free. We are thus led to conclude that the chemical attraction between iron and sulphur is greater than that between mercury and sulphur. So, too, if a strip of zinc is placed in a solution of copper chloride, the greenish-blue solution of this substance becomes after a time colourless, and a red powder, seen at once to be metallic copper, is deposited. Here the zinc, having a greater attraction for the chlorine than the copper, expels the copper from the copper chloride, forming zinc chloride, which is colourless and remains in solution, and sets free the copper.

3. **Simple and compound substances.**—If we take the substance known as *red precipitate* and expose it to the action of heat, we shall find it ultimately resolved into a bright white liquid metal, which is easily recognised as mercury, and into a gas in which bodies will burn as in air, but with far greater brilliancy. This gas is known as oxygen. By the further application of heat, or, indeed, of any other physical agent, to either of these substances, we can get from mercury nothing but mercury, and from oxygen nothing but oxygen. We are entitled in the present state of our knowledge to regard these as ***simple*** or ***elementary*** forms of matter, and they are spoken of as ***elements***.

4. **Atoms. Combining weights.**—If we mix together sulphur and iron, each in a fine state of division, we may do so in any proportion ; if we apply a magnet to the mixture it will remove the

particles of iron and leave the sulphur ; or if we treat the mixture with carbon bisulphide it will dissolve out the sulphur and leave the iron unaltered ; we can, in short, by physical means separate the two constituents. But if we heat the mixture the two substances combine to form a new compound, different in properties from its constituents ; the sulphur can no longer be dissolved out, nor can the iron be withdrawn by a magnet. The compound formed is iron sulphide, and if it be examined it will always be found to contain iron and sulphur in the ratio of seven parts by weight of iron to four of sulphur, and if either of the substances be in excess, however great, of these proportions, the excess could be removed by purely physical means, leaving the iron sulphide unaltered ; and we cannot get the constituents from the iron sulphide except by circuitous chemical processes.

In the present state of our knowledge it is assumed that the divisibility of matter is not infinite ; that if we used methods of division far more perfect than those now at our disposal, we should arrive at a certain limit which could not be passed, viz. at the *atom* which could be conceived as being impenetrable, incompressible, inexpansible, and as possessing a definite weight, which characterises it. When an atom enters into combination with the atom of another body it does so only with this weight, or an integral multiple of it. This is called the *atomic weight*, or combining weight of the element. Thus, that of hydrogen is 1, carbon 12, oxygen 16, silver 108, gold 197.

5. **Molecules.**—Matter in the form presented to us is made up of groups, each containing two or more atoms, which are called *molecules*. Chemical forces can resolve molecules into atoms ; physical forces operate only on the molecule as a whole. With most elements the molecule consists of two atoms. The molecule of a compound substance is an aggregate of the atoms of its constituents. Two atoms of hydrogen and one of oxygen unite to form a molecule—not an atom—of water ; the molecule of marsh gas consists of four atoms of hydrogen and one of carbon. Sulphuric acid contains one atom of sulphur, four of oxygen, and two of hydrogen in the molecule.

Neither the molecules nor the atoms are accessible to direct observation. They are of almost inconceivable minuteness, yet, by various trains of reasoning from known phenomena, it has been possible to arrive at an approximate determination of their size. Thus, it has been calculated that a cubic millimetre of water, which

is about the size of a pin's head, would contain a number of molecules equal to the cube of a million: that is, a number approximately represented by unity followed by eighteen zeros. Even in gases, where the number is far smaller, there are under ordinary conditions not less than 20 trillions of molecules in a cubic centimetre.

To form an idea of the degree of the size of the molecules Lord Kelvin gives this illustration :—'Imagine a drop of rain, or a glass sphere the size of a pea, magnified to the size of the earth, the molecules in it being increased in the same proportion. The structure of the mass would then be coarser than that of a heap of fine shot, but probably not so coarse as that of a heap of cricket balls.'

6. **Intermolecular Spaces. Ether.**—If we exert a pull in opposite directions on the two ends of a rod, the rod is lengthened, and when pressure is applied it is shortened; the volume of a body is increased by a rise, and is lessened by a fall, in temperature. Such facts as these are best explained by supposing that the molecules of which a body is built up are not in actual contact. Again, if we mix equal volumes of alcohol and water the volume of the mixture is less than the sum of the volumes of its constituents, and when a salt is dissolved in water there is no corresponding increase in volume. The most natural interpretation of these facts is that the molecules of each substance penetrate into the interstices of the other.

Hence, on the basis of these and other facts, it is assumed that the molecules of all bodies, the hardest and the densest, are at appreciable distances from each other, which distances may be increased or diminished by the influence of external physical forces, without the molecules themselves being altered. The space by which the molecules are separated are spoken of as ***intermolecular spaces***, and the forces between the molecules are known as molecular forces, which act only at almost infinitely small distances.

It is further assumed that the intermolecular spaces of all bodies, the softest and the hardest, the lightest and the heaviest, the celestial spaces and the most perfect vacuum attainable, are filled by a subtle, perfectly elastic, incompressible fluid of extreme tenuity, which is known as the ***ether***.

We shall afterwards see that sound is transmitted in gases by a vibratory motion of the particles of air (171), and, in like manner, it has been made out that light and radiant heat are transmitted by a state of vibration of this ether. Recent discoveries also

have established the fact that electricity is transmitted through ether in the same way; the difference being in the rapidity of the vibratory motion. Whether the ether has other functions or not cannot at present be determined. The ready explanation of luminous and electric phenomena which the hypothesis of this ether furnishes, is the justification for assuming its existence.

7. **Different states of matter.**—All substances present characters in virtue of which they may be divided into three distinct classes—*solids*, *liquids*, and *gases*.

The particular form which matter assumes—whether solid, liquid, or gaseous—depends on the extent to which it is influenced by the force of molecular attraction, which tends to bring the molecules nearer each other, and also upon its temperature, the effect of rise of temperature being as a rule to force the molecules further apart.

Solids, such as wood, stones, metals, etc., are substances which are more or less hard, and retain the form which they possess naturally or which has been given them by art. In solids the molecules have very little freedom of motion. They are capable of vibrating, but cannot move away from one part of the substance to another.

Liquids, such as water, oil, mercury, are bodies which have no hardness, and present but little resistance when a body is immersed in them; they have no shape of their own, but at once take that of the vessels in which they are contained, in which they have a free surface; they are virtually incompressible. The molecules are able not only to vibrate, but to move freely past each other from one part of the mass to another.

Gases, such as hydrogen, oxygen, carbonic acid, are also called *aëriform fluids*, from their analogy with our air, which is a mixture of oxygen and nitrogen. They are very light bodies; excepting a small number, which are coloured, they are invisible; and hence a vessel filled with air, hydrogen, or any colourless gas, appears quite empty. Like liquids, they have no shape of their own, but, unlike liquids, they have no free surface and are eminently compressible and expansive. In gases the molecules dart about freely in all directions, each molecule moving in a straight line until its direction is altered by an encounter with another molecule or the side of the containing vessel. Attraction between neighbouring molecules is only experienced when they come very close together in an encounter. Sometimes it is said that the continual tendency of a

gas to expand is due to a mutual repulsive action between the molecules. It is not, however, necessary to assume any such repulsion. Gases are continually tending to occupy a larger space. This property will be described as the ***expansibility*** of gases (120).

There are many bodies which can exist in all these three different forms. Thus, water, exposed to great cold, becomes solid in the form of ice; at ordinary temperatures it is liquid, while at higher temperatures it becomes a gas. Sulphur, iodine, and several of the metals, such as mercury and zinc, present the same phenomena. Most substances, however, especially compound bodies, are not capable of existing in more states than one, since, by a sufficient increase of temperature, they are decomposed.

CHAPTER II

GENERAL PROPERTIES OF BODIES

8. **Extension.**—By *general properties* we understand those which are common to all bodies, whether solids, liquids, or gases; such, for instance, are *extension*, *impenetrability*, *divisibility*, *porosity*, *compressibility*, *elasticity*, *inertia*, and *gravity*.

Specific properties are such as we observe only in certain bodies, or in certain states of these bodies; *solidity*, *fluidity*, *tenacity*, *malleability*, *colour*, *hardness*, etc., are properties of this class.

The first general property of bodies with which we are concerned is their *extension* or *magnitude*: that is, that every body occupies a certain space. All bodies, even the smallest atoms, have a certain extension.

Extension considered in only one direction, that of length, gives a *line*; in two directions, length and breadth, a *surface*; and, in the three directions, length, breadth, and thickness, a *volume.*

With respect to the above general properties, it may be remarked that *impenetrability* and *extension* might be more aptly termed essential attributes of matter, since they suffice to define it; and that divisibility, porosity, compressibility, and elasticity do not apply to atoms, but only to bodies or aggregates of atoms.

9. **Impenetrability.**—This is the property in virtue of which one portion of matter occupies space to the exclusion of all other. Strictly speaking, this property only applies to the atoms of bodies.

In many phenomena bodies appear to penetrate each other. Thus, if a pint of water and a pint of alcohol be mixed together, the volume of the mixture is less than two pints. A similar contraction occurs in the formation of certain alloys; for instance, brass, which is an alloy of copper and zinc, occupies a less volume than the united volumes of its constituents.

This penetration is, however, only apparent, and is due to an alteration in the position of the molecules; they come nearer

each other, and the space occupied by the molecular pores is diminished.

A nail driven into wood is not a true case of penetration. The molecules of the wood are driven apart by the nail, but wherever it has penetrated there is no wood. When water is poured upon a heap of sand, it at once disappears ; the water, however, does not penetrate the substance of the sand itself, but merely fills the space between the grains.

If we plunge the hand in water the liquid moves away and gives place to the hand.

When a glass tumbler is dipped into water with the mouth downwards, the volume of air inside diminishes ; this experiment proves that air is compressible, but not that it is penetrable.

If a glass funnel finely drawn out be fitted in the neck of a bottle, water cannot be poured into the bottle, for the enclosed air cannot escape. In casting iron, the moulds must have air-holes to allow the air to escape.

10. **Divisibility.**—This is the property which all bodies have of being divided into distinct parts.

Numerous examples may be cited of the extreme divisibility of matter.

A piece of carmine not larger than a grain of corn gives a distinct colour to two gallons of water ; from which it can be deduced that this small quantity of colouring matter cannot contain less than ten million particles.

Blood is composed of red, flattened globules floating in a colourless liquid called *serum*. In man the diameter of one of these globules is less than the 3,500th part of an inch, and the drop of blood which might be suspended from a point of a needle would contain about a million of globules.

By dissolving in alcohol a known weight of fuchsine, and diluting the liquid, it was observed that a solution containing not more than $0\cdot00000002$, or, as it may conveniently be written, $0\cdot0_{7}2$, of a gramme in one cubic centimetre had still a distinct colour : that is, that a weight of not more than the one fifty-two-millionth of a gramme can be perceived by the naked eye. As the molecular weight of this substance is 337 times that of hydrogen, it follows that the weight of an atom of hydrogen cannot be greater than the one 20,000-millionth of a gramme.

Still greater is the divisibility of some bodies possessing an odour. The tenth part of a grain of musk will continue for years

to fill a room with its odoriferous particles, and at the end of that time will scarcely be diminished in weight. According to the experiments of Kreil, a cubic centimetre of asafœtida can furnish 1,200 billion distinct particles.

11. **Porosity.**—The intermolecular spaces, sometimes called molecular pores, of which we have spoken (6), cannot be distinguished by even the most powerful microscopes. They are not to be confounded with the small tubes or channels which we can see by the naked eye in such substances as sponge, pumice stone, etc., and in others, such as in animal or vegetable fibres, by the use of a moderate magnifying power; these form actual cavities across which molecular forces cannot act, and are spoken of as *pores*, and *porosity* is the property which bodies possess of having visible pores. Porosity of this kind is not a universal property of matter—it is absent in glass, for instance.

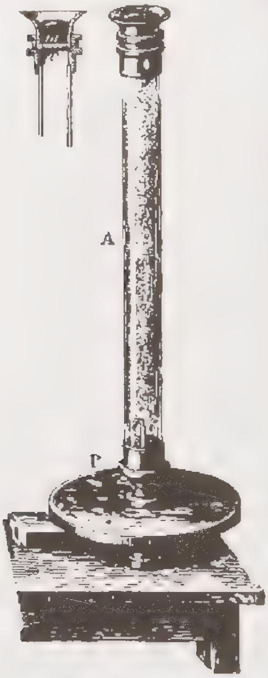


Fig. 1.

The existence of sensible pores may be shown by the following experiment, which is known as the *mercury rain*. A long glass tube, A (fig. 1), is provided with a brass cup, *m*, at the top, and a brass foot made to screw on to the plate, P, of an air-pump. The bottom of the cup consists of a thick piece of leather, *o*. After pouring mercury into the cup so as entirely to cover the leather, the air-pump is worked, and a partial vacuum produced in the tube. As a consequence a shower of mercury is at once produced within the tube, for the atmospheric pressure on the mercury forces that liquid through the pores of the leather. In the same manner water or mercury may be forced through the pores of wood, if the leather in the above experiment be replaced by a disc of wood cut perpendicularly to the fibres.

When a piece of chalk is thrown into water, air-bubbles at

once rise to the surface, in consequence of the air in the pores or the chalk being expelled by the water. The chalk will be found to be heavier after immersion than it was before, and from the increase of its weight the volume of its pores may be deduced.

12. **Applications of porosity.**—The property of porosity is frequently utilised, more especially in the process of *filtration*. This consists in clarifying liquids by freeing them from particles of matter which they hold in suspension; as is done, for instance, with river-water, which is turbid, owing to the earthy matter it carries along with it.

The apparatus used for this purpose are called *filters*, and are usually constructed of unsized paper, felt, charcoal, etc. The pores of these substances are sufficiently large to allow liquids to pass, but small enough to arrest the particles held in suspension.

Fig. 2 represents a simple form of filter. It is a conical felt bag, suspended by three cords, into which is poured the turbid liquor, which slowly traverses the pores, while all the solid particles to which the turbidity is due remain behind on the filter. This method is well adapted for clarifying syrups, jellies, and liqueurs.

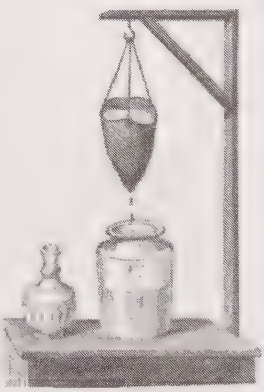


Fig. 2.

Layers of powdered wood-charcoal are also used for filtration. A layer of sand or of broken glass produces the same effect. The clearness of deep-well water is due to its filtration through thick strata of earth.

13. **Compressibility.**—This is the property which bodies possess of being diminished in volume by pressure without undergoing any loss of mass. Being due to the approach of the molecules towards each other, it is both a consequence and a proof of the existence of intermolecular spaces.

Compressibility is very marked in sponge, india rubber, cork, pith, paper, cloth, etc. The volume of these substances is considerably diminished by mere pressure between the fingers. The compressibility of metals is proved by the impression which they receive from the die, in the process of coinage. There is, in most

cases, a limit beyond which, when the pressure is increased, solids are fractured or reduced to powder.

The compressibility of liquids is so small as to have remained for a long time undetected; it may, however, be proved by experiment, as will be seen in the chapter on HYDROSTATICS (84).

The most compressible bodies are gases, which by pressure may be made to occupy ten, twenty, or a hundred times less space than under ordinary circumstances. The great compressibility of gases may be demonstrated by means of a glass tube with very thick sides closed at one end, and provided with a tightly fitting solid piston (fig. 3). The enclosed air cannot escape, and yet, when the handle of the piston is pressed, it can be moved down to one-half or to three-quarters the length of the tube; proving that the volume of the air is reduced to half or a quarter what it was originally.

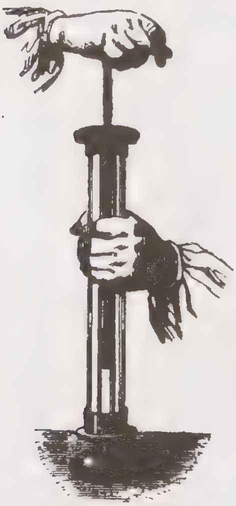


Fig. 3.

14. **Elasticity.**—*Elasticity* is the property which bodies possess of resuming their original form or volume, when, after having been compressed, bent, twisted, or pulled, the force which altered them has ceased to act.

The elasticity of the body is measured by the resistance which it opposes to any force or stress tending to deform it. Four kinds of elasticity may be distinguished:—(1) that exhibited by gases and liquids when the applied stress is a *pressure*; (2) the elasticity of *flexure* or *bending*, exhibited by springs; (3) that of *torsion* or *twisting*, which is developed in linen or cotton threads when they are untwisted; and (4) the elasticity of *tension* or *stretching*, which is that of piano or violin strings when they are stretched.

Whatever be the kind of elasticity, it is always due to a displacement of the molecules. If the molecules have been brought nearer by pressure, heat tends to separate them; if, on the contrary, they have been separated, molecular attraction tends to bring them near each other again. If a piece of whalebone be bent, the

molecules in the concave part, being compressed, repel each other; in the convex part, where they are separated, they tend to approach each other; both these actions concur, therefore, in straightening it as soon as it is free.

Gases and liquids are perfectly elastic in the sense that they regain exactly their original volume when the pressure to which they have been subjected is removed. But if elasticity is measured by the stress (pressure) required to produce a given deformation (in this case a given diminution of volume), we must regard liquids as having much greater elasticity than gases, since they are much less compressible. Solid bodies present different degrees of elasticity; for example, glass, steel, ivory, marble, are highly elastic; lead, clay, and fats possess scarcely any elasticity.

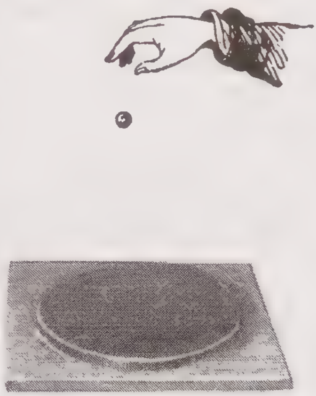


Fig. 4.

India rubber has wide limits of elasticity. An india rubber string may be stretched to two or three times its length, and regain its original length when the tension is removed. But when stretched beyond a certain point or stretched often, it is permanently altered. Glass is much more elastic than india rubber, but its elastic limits are much narrower; except in very thin strips or fine threads, it will not bend far without breaking. In gases and liquids, on the contrary, no such limit can be reached: they always regain their original volume when the original condition of pressure is restored.

The difference between the elastic limits of steel and wood may be seen by bending to the same extent two similar strips of those substances; when released the steel reverts at once to its original straight form, whilst the wood is permanently curved.

The elasticity of solids may be shown by the following experiment: On a slab of polished black marble, thinly smeared with oil, an ivory ball is allowed to drop from gradually increasing heights. Each time it will rebound and rise to a height a little less than that from which it fell, after having formed on the layer of oil

a circular impression which is larger the greater the height of the fall (fig. 4). From this we conclude that the ball was flattened each time, and that it rebounded in consequence of the reaction of its compressed molecules.

15. **Illustrations of elasticity.**—Numerous illustrations of the property of elasticity may be mentioned. It is owing to their elasticity that corks are used for closing bottles. When they are forcibly pushed into the neck they become compressed, and then, their elasticity causing them to press against the sides, they completely close the neck. When the string of a cross-bow is stretched its elasticity is brought into play, and the velocity imparted to the bolt when the string is released represents the work done in stretching it.

Children's balls depend upon the elasticity of gas : they are made of india rubber, and are inflated by air; when they strike against the ground, or against a wall, their volume diminishes, and the air which they contain being suddenly compressed, expands, and, acting like a spring, makes the ball rebound. A similar application is met with in air-cushions. They are made of an air-tight material, and, being inflated by air, are both compressible and elastic, and thus form a very soft seat.

Fig. 5.

The use of carriage and of watch and clock springs depends upon the elasticity of steel. In like manner the elasticity of wool, hair, feathers, is made use of in mattresses, pillows, and seats. The strong spiral steel springs in the buffers of railway carriages are further illustrations.

The letter weight (fig. 5), the construction of which will be at once understood, is an application of elasticity; the dynamometer (fig. 8) also depends on the elasticity of a steel band.

It is, lastly, in consequence of their elasticity that piano, guitar, or violin strings are capable of being made to vibrate, which, as we shall show, is the origin of the sounds which stringed instruments yield.

CHAPTER III

MOTION AND FORCE

16. **Rest and motion.**—A body is said to be at *rest* when it remains in the same place; to be in *motion* when it passes from one place to another. Both rest and motion are either absolute or relative.

Absolute rest would be the entire absence of motion. No such condition, however, is known in the universe; for the earth and the other planets rotate both about the sun and about their own axes, and therefore all the parts composing them share this double motion. Even the sun itself has a motion of rotation which excludes the idea of absolute rest.

Relative or *apparent rest* is the condition of a body which appears fixed in reference to surrounding objects, but which really shares with them a double motion. For instance, a passenger in a railway carriage may be in a state of relative rest with respect to the train in which he travels, but he is in a state of relative motion with respect to the objects (fields, houses, etc.) past which the train rushes. These houses, etc., again, enjoy merely a state of relative rest, for the earth itself which bears them is in a state of incessant relative motion with respect to the celestial bodies of our solar system.

The absolute motion of this passenger would be that measured in regard to a fixed point in space; this, however, cannot be realised, for we know no such point. In short, absolute motion and rest are unknown to us: in nature, relative motion and rest are alone presented to our observation.

17. **Different kinds of motion.**—Motion is either rectilinear or curvilinear: *rectilinear* when the moving body travels along a straight line, as when a body falls to the ground; *curvilinear* when it goes along a curved line, as in the case of a horse turning in a mill.

Each kind of motion is either *uniform* or *varied.*

18. **Uniform motion.**—Motion is said to be uniform when the moving body passes over equal spaces in equal intervals of time: such, for instance, as the motion of a water-wheel when it makes exactly the same number of turns in a minute. Such, again, is the motion of a hand of a watch.

The *velocity* of a moving body is the space traversed by the body in a given time, a second or an hour, for example. A bullet which, fired from a gun, passes through 1,200 feet in every second is said to have a velocity of 1,200 feet per second. A train which moves 30 miles in each successive hour is said to have a velocity of 30 miles an hour, or 44 feet per second.

19. **Varied motion.**—Varied motion is that in which unequal spaces are traversed in equal times. If the spaces traversed in the same time go on increasing, the motion is said to be *accelerated*; such is the motion of a train starting from a station: if the spaces decrease, as in the case when a train comes into a station, the motion is *retarded.*

If a body moves in such a way that the velocities gained by it in equal times are equal, its motion is said to be *uniformly accelerated*; if, on the other hand, its velocity diminishes in proportion to the time, the motion is *uniformly retarded.* We shall soon see examples of these kinds of motion in the case of falling bodies.

20. **Inertia.**—*Inertia* is a purely negative property of matter; it is the incapability of matter to change its own state of motion or of rest.

Daily observation shows that a body never spontaneously passes from a state of rest into one of motion. Bodies in falling to the ground seem to set themselves in motion. This is, however, not in consequence of any inherent property; but, as we shall afterwards see, because they are acted upon by the force of gravity.

Not merely do bodies at rest persist in a state of rest, but bodies when put in motion by the action of any force continue to move. This principle may seem less obvious than the former, because we are accustomed to see bodies gradually move more slowly, and ultimately stop, as is the case with a billiard-ball, for example. But this is not due to any inherent preference for a state of rest on the part of the billiard-ball, but because the motion originally imparted to it is impeded by the friction of the cloth on which it rolls, and by the resistance of the air. The smaller these resistances, the more prolonged is its motion; as is observed, for

instance, if a ball be set rolling on a smooth sheet of ice. If all impeding causes could be removed, such as friction against the supports and the resistance of the air, a body once in motion would continue to move for ever. Only in the case of the heavenly bodies are such conditions met with.

21. **Effects due to inertia.**—Numerous phenomena may be explained by the inertia of matter. For instance, before leaping a ditch we run towards it, in order that the motion of our bodies at the time of leaping may add itself to the muscular effort then made.

On descending carelessly from a carriage in motion, the upper part of the body retains its motion, whilst the feet are prevented from doing so by friction against the ground ; the consequence is we fall towards the moving carriage.

If a man, in running, strikes his foot against an obstacle, he is apt to fall forwards, because the rest of his body tends to retain the motion it has acquired. When a horse at full gallop suddenly stops, if the rider does not sit tight with his knees, he is thrown over the horse's head, in virtue of his inertia. A grindstone only gradually acquires its full speed, but then continues its motion even after the force has ceased to act.

The terrible accidents on our railways are chiefly due to inertia. When the motion of the engine is suddenly stopped, by a train leaving the line for instance, the carriages strive to continue the motion they had acquired, and in doing so are shattered against each other.

The action of projectiles is another case. When a bullet traverses a wall, it is owing to its tendency to retain the velocity which the explosion of the powder had imparted to it. In the action of hammers, and of pile-driving, we have analogous cases.

A coin is laid on a card which covers a wide-necked bottle ; on flipping or snatching the card away the coin drops into the bottle ; the motion of the card is so rapid that it is not imparted to the coin. A bullet fired against a window-pane makes a clean hole in it, while the pane is smashed by a less violent blow. So, too, a bullet can be shot through a board placed vertically without overturning it, for which otherwise only the smallest force might be needed.

The actions of beating a coat with a stick to expel dust ; of shaking the snow from our shoes by kicking against the door-post ; of cleaning a dusty book by striking it against another, all depend

on inertia. Driving a *hoop*, spinning a *top*, and other toys are further illustrations.

22. **Force, resistance.**—Bodies being of themselves inert, and having no tendency to change their state either of rest or of motion, any cause capable of making them pass from a state of rest to one of motion, or conversely from a state of motion to one of rest, is called a *force*.

The attraction exerted between the molecules of bodies and the muscular action which men and animals bring into play are forces ; magnetic and electric attractions and repulsions are forces ; gravity is a force, as is also the elasticity of gases and vapours, which we shall subsequently deal with.

The forces which tend to resist or destroy motion are called *resistances*. Thus, when a man drags a burden along the ground, the friction of the burden against the ground acting against the force due to his muscular action is a resistance.

When force is applied to a body motion of the body will ensue, unless the applied force is balanced by an equal force acting in the opposite direction. The weight of a book resting on a table is a force acting vertically downwards which is exactly balanced by the reaction of the table acting vertically upwards. When a body is not supported, gravity causes it to fall vertically with uniform acceleration, which at the same place is constant for all bodies and is called g. In general, when a force P is applied to a body of mass m, and causes that mass to move with acceleration a, we have the relation $P = ma$. If the force acting is the weight of the body, the acceleration is g, and the formula becomes $W = mg$.

23. **Friction.**—Suppose a wooden box, A, the bottom of which is planed smooth, to be placed on a wooden table, B, also smoothly polished, and that to the box is fastened a string which passes over a pulley, C, and to it is attached a scale-pan, D (fig. 6). If the box be loaded so that the total weight is 100 ounces, for instance, it will be found that weights must be added to the scale-pan until the total weight is about 50 ounces, in order to move the box in a horizontal direction along the table. If the total weight of the box be 200 ounces, the weight required to move it

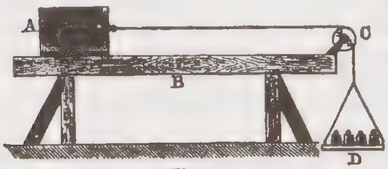


Fig. 6.

will be 100 ounces. If the table were a perfectly smooth polished iron plate, and the bottom of the box were shod with the same material, a weight of only 30 ounces would be sufficient to move the box.

The resistance which is thus offered to motion is called *friction.*

The surfaces of bodies are never perfectly smooth ; even the smoothest possess roughnesses which cannot be detected by the touch or by ordinary sight ; and *friction* consists in the fact that the body must be raised over these obstacles or must break them down. They fit in each other as if they were toothed wheels.

The number which tells what proportion of the total weight must be applied simply to overcome friction is called the *coefficient of friction.* Thus, the coefficient of friction between polished wooden surfaces is, as we have seen, about one half, between polished iron surfaces about one third, and so on. The friction between two substances of the same kind is greater than that between two different ones which have different structures.

Friction is of two kinds : *sliding*, in which one body *slides* over another, as in the above case, or when a box is dragged along a floor—it is least when the two surfaces are always in contact, as in the motion of an axle in its bearing ; and *rolling* friction, as when a cylindrical body moves over a horizontal surface, like an ordinary wheel on a road. In cycles the axles are made to play on ball bearings so as to diminish friction.

In all machines, part of the work is expended in overcoming the unavoidable resistance due to friction ; it is thereby converted into heat (313), and thus becomes useless. To lessen this friction, the surfaces in contact are rubbed with substances, usually of a fatty nature, which fill up the inequalities and make the surfaces smooth. Moisture and oil increase the friction of wood, for they are absorbed by it ; while tallow, soap, and blacklead lessen it. Oil and lard lessen the friction of metallic surfaces. Rolling friction is less than sliding friction, hence the use of castors on pianos and other heavy furniture, and of rollers placed under large blocks of stone or trunks of trees. This, however, is not always so ; thus a sledge experiences less friction on snow than a carriage, for in this case the wheels sink, and friction on the sides results. It is sometimes desirable to increase friction, as when ashes or sand are strewn on ice, or on an inclined railway after rain, or when a violin bow is rubbed with resin ; again, rolling is sometimes changed into sliding friction, in order to increase it, as when a drag

is applied to a wheel. The friction of carriage-wheels is less the greater the diameter of the wheel, and the less that of the axle.

The work done in moving goods along a level road consists in overcoming friction. On a good road the friction amounts to a twentieth, and on iron rails to a two-hundredth part of the load ; so that a horse or an engine can draw ten times as much on the latter as on the former.

Friction is independent of the extent of the surfaces in contact if the pressure is the same. Thus, suppose a board with a surface of 12 square inches resting on another board to be loaded with a weight of one pound. If this load be distributed over a similar board of 24 square inches surface, the total friction will be the same, for while the friction per square inch is one-half, the pressure on each square centimetre is one-half of what it was before. So, too, a rectangular stone experiences the same friction whether it is laid on the narrow or on the broad side.

Without friction on the ground neither man nor animals, neither ordinary carriages nor railway carriages, could move ; without friction motion could not be transmitted by bands from one machine to another ; without it no book would remain on a desk, no nail could be fixed ; and without it we could hold nothing in the hands.

Gases also, and still more liquids, offer frictional resistance to motion. If it were not for the resistance offered by the air, a hailstone half an inch in diameter, falling from the height of a mile, would have a velocity of over 400 feet in a second, or that of a pistol bullet, whereas its actual velocity is probably not more than one-twelfth of this amount.

In a descent made by the aëronaut Sirel in a parachute (168) he took forty-five minutes to fall through a height of 5,900 feet ; apart from friction by the air, the time required as calculated from the laws of falling bodies would have been nineteen seconds, so that the rate of falling was only $\frac{1}{140}$ of what it would be in a vacuum.

For moderate velocities the friction varies approximately as the square of the velocity ; for greater velocities more nearly as the cube.

It is this resistance which so greatly increases the difficulty and cost of attaining very high speeds in steam-vessels, to which must be added the production of waves on the surface and of eddy currents.

Without friction no knot could be made, and no woven or knitted fabric would hold together. Friction enables us to form long threads or ropes from the comparatively short fibres of cotton or hemp; for it is the friction due to the twisted fibres which keeps the materials together. A violin bow is rubbed with resin, so that by increasing the friction against the strings it may put them in motion.

24. **Distinctive characters of forces.**—Three things are to be distinguished in every force—the point of application, the direction, and the intensity.

The *point of application of a force* is the point at which it exerts its action. Having attached a cord to a sledge, as shown in fig. 7, the point of application of the force active along it is the point A, at which the cord is actually attached.

The *direction of a force* is the right line along which it urges

Fig. 7.

or tends to urge the point of application. In fig. 7, the cord AB represents the direction of the force.

The *intensity of a force* is its magnitude, or value, in reference to a certain standard. In fig. 7, which represents a horse drawing a cask on a sledge, a certain exertion of force is required on the part of the horse; if the sledge were loaded twice or thrice as much, the force required must be twice or thrice as great.

Forces which only act for a very short time on a body, as in the case of an impact or the explosion of gunpowder, are called *instantaneous* forces or *impulses*; those which act throughout the whole of the movement are called *continuous*. These are not two kinds of forces, but simply two modes of action of forces.

25. **Measurement of force. Dynamometer.**—The force which is exerted in pushing or drawing a body is measured by the

number of pounds necessary to produce the same pull ; so that a force is said to be a force of 40 or 50 pounds, when it can be replaced by the action of a weight of 40 or 50 pounds.

The weight which thus represents the intensity of a force is determined by means of the *dynamometer*. There are several forms of this instrument, one of the simplest being that represented in fig. 8. It consists of a V-shaped plate of tempered steel, AB. At one end of the arm B is fixed an iron arc, *n*, which passes freely through an aperture at the end of the arm A. To this latter is fixed an arc, *m*, fitting in the same manner in the arm B. The arc *m* is provided at the end with a crook, and *n* with a ring, and

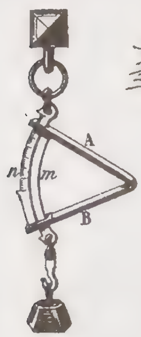


Fig. 8.

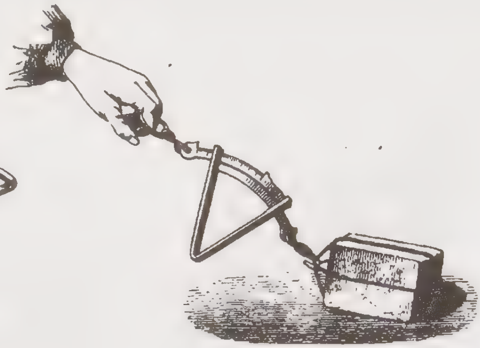


Fig. 9.

on the latter, *n*, there is a graduation obtained in the following manner :—

The apparatus being fixed to a resisting support, weights of 1, 2, 3, 4, or more pounds are successively suspended to the crook. The arm B, supported by the arc *n*, remains fixed, while the arm A, being moved by the weight attached to the arc *m*, is lowered to an extent dependent on the weight. The load is gradually increased until it has reached the utmost limit possible without breaking, care being taken at each load to mark a line on the arc *n* at the point at which the arm A stops.

In order to apply it to the measurement of forces—to estimate, for instance, the effort necessary to drag a load (fig. 9)—the crook of the arc *m* is fixed to the load ; then, holding in the hand the ring of the arc *n*, it is pulled until the load is moved. The bending of

the arm A marks on the arc n the value in pounds of the effort of traction.

In this way, for instance, the pull exerted by a horse in drawing a plough may be measured by attaching one end to the plough and the other to the whipple-tree. The amount of pull in average soil and average depth of ploughing may be taken at about five hundredweights. In like manner, the friction of steel upon smooth ice has been determined by a skater holding in his hand a spring balance attached to a cord by which he was drawn along by a second skater. At starting the spiral showed a pull of 10 to 11 pounds, but during the motion this varied from 2 to 4 pounds. As the weight of the skater was 136 pounds, the coefficient of friction during the motion was $\frac{1}{68}$ to $\frac{3}{68}$, or 1·5 to 3 per cent.

The apparatus described (fig. 8) may also be used instead of a balance to determine the weight of bodies.

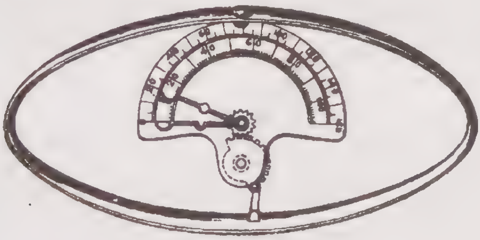


Fig. 10.

A form of dynamometer used to test the muscular strength of the hands is represented in fig. 10. It is an elliptical steel spring which is pressed between the hands : the motion thus produced is transmitted by means of a rackwork to a small toothed-wheel which moves an index over a scale. This index moves a second one, which stops at the division attained, and remains there after the compression has ceased.

Salter's *Spring Balance* is another form of dynamometer. It consists of a stiff spiral of wire like a corkscrew, fixed at its upper end and carrying below a hook for suspending weights, and a pointer which moves over a graduated scale. As the elongation of the spring is proportional to the stretching force, the amount of the latter may be read off from the uniformly graduated scale.

26. **Resultant and component forces.**—When a body is acted upon by only a single force, it is clear that, if it is not hindered by

any obstacle, it will move in the direction of this force ; but if it is simultaneously acted upon by several forces in different directions, its own direction will not, speaking generally, coincide with that of any one of these forces. If two men, for example, on the opposite banks of a river, tow a boat by means of ropes, as shown in fig. 11, the boat follows neither the direction AB nor the direction AC, in which these men are respectively pulling, but takes an inter-

Fig. 11.

mediate direction, AE ; that is, it moves as if it were acted upon by a single force in the direction AE.

As the single force, which we conceive as having the direction AE, produces the same effect as the forces of traction of these two men, it is called the *resultant* of these two forces ; and, conversely, these, in reference to their resultant, are spoken of as the *components*.

27. **Value of the resultant of two concurrent forces. Parallelogram of forces.**—When two forces having different directions are applied to the same point of a body, as represented in fig. 11, there is a very simple ratio between their intensities and that of their resultant, which is of great importance from the number of its applications.

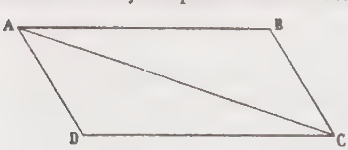


Fig. 12.

It will first of all be necessary to define the word *parallelogram*, of which we shall make use. The parallelogram is a geometrical figure, whose opposite sides are equal and parallel (fig. 12)—that is, the two lines AB and DC are equal and parallel, and also the lines AD and BC. These lines form

the *sides* of the parallelogram, and the points A, B, C, D, the *angles*. The *diagonal* is the line AC, joining two opposite angles A and C.

In treatises on mechanics, proofs are given of the following important theorem, which is known as the *principle of the parallelogram of forces.*

When two forces applied at the same point A (fig. 13) *are represented, in direction and in magnitude, by the sides* AB *and* AD *of the parallelogram* A B C D, *their resultant is represented both as to its direction and magnitude by the diagonal* AC *of this parallelogram.*

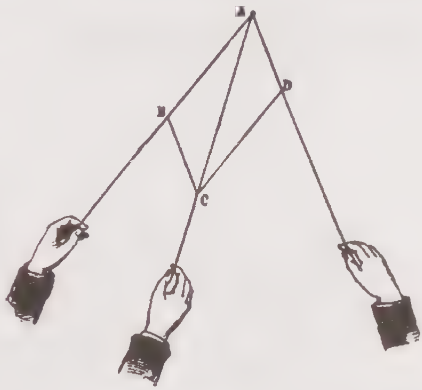


Fig. 13.

That is, that the point A being simultaneously acted upon by two forces, whose directions and intensities are respectively represented by AB and AD, moves in the direction AC exactly as if it were acted upon by a single force, the direction and intensity of which are represented by the line AC.

Frequent applications are met with of the principle of the parallelogram of forces. Thus, in the flight of a bird, when the wings strike against the air, a resistance is offered which is equal to impulsive forces from back to front in the direction AH and AK (fig. 14); hence, representing by AB and AD the intensities and directions of these impulsive forces, if the parallelogram be completed, we shall find that the resultant, or the single force which makes the bird advance, is represented in direction and magnitude by the diagonal AC. The same reasoning applies to the swimming both of men and of fishes.

28. **Another effect of the parallelogram of forces.**—We have seen that, in accordance with the principle of the parallelogram of forces, two forces applied at the same point of a body may be reduced to a single one. By the aid of the same principle, a single force applied to a body may be considered to be replaced by two other

forces producing together the same effect as the first. This force is then said to be *resolved* into two others.

It is but seldom indeed that the action of a force is entirely utilised; it may almost always be considered as decomposed into two others, only one of which produces a useful effect. Thus when the wind blows against the sails of a vessel, not quite directly, but a little on one side, as shown in fig. 15, the effect of the wind in the direction *va* may be considered to be resolved into two others, one in the direction *ca*, and the other in a lateral direction *ba*, of which the first moves the vessel. The second only guides it.

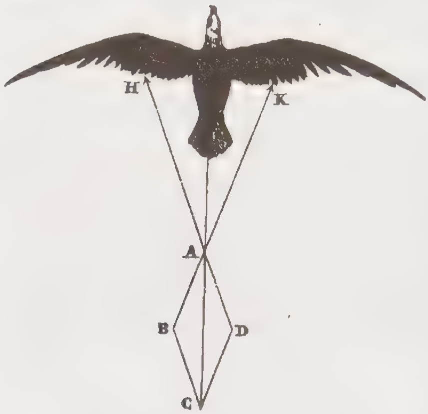


Fig. 14.

29. **Cases in which the forces are parallel. Value of the resultant.**—In the case of the boat drawn by a rope (fig. 11), the forces were *concurrent*—that is, their directions, if produced, would meet in one point; but it may happen that the forces applied to the same body are parallel, and then two cases present themselves: that is, they either act in the same direction, as in the case of two horses drawing a carriage; or they may act in opposite directions. When a steamer, for instance, ascends a river, the current acts in opposition to the force which urges the steamer. It can be proved that in the first case *the resultant of the forces is equal to their sum*; and that in the second *it is equal to their difference.*

Thus, if the speed of a Rhine steamer is 10 miles an hour, and the velocity of the current is $2\frac{1}{4}$ miles an hour, then the steamer will go *with* the current at the rate of $12\frac{1}{4}$ miles, and *against* it at the rate of $7\frac{3}{4}$ miles an hour.

30. **Equilibrium of forces.**—When several forces act upon a body at the same time, they do not always put it in motion; it may happen that while some of these forces tend to produce motion in a

certain direction, the others tend to produce an equal motion in the opposite direction. It is clear that in this case, since the forces just neutralise each other, no effect can be produced. Whenever several forces applied to the same body thus mutually neutralise each other, we have what is called *equilibrium*.

The simplest case of equilibrium is that of two equal and opposite forces applied at the same point of a body. For instance, if two men pull at a cord with the same intensity, one in one direction, and the other in the opposite one, equilibrium will be produced

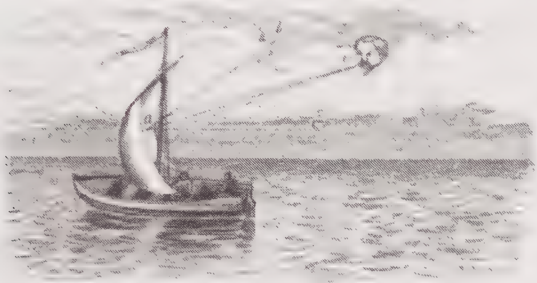


Fig. 15.

(fig. 16). In like manner, if, in a well, two buckets of the same size, each full of water, are suspended at the end of a rope which passes round a pulley, the weight of one holds the other in equilibrium.

The bodies which we consider ordinarily to be in a state of rest are really in a state of equilibrium. For instance, when a body

Fig. 16.

rests on a table, there is equilibrium between the force of gravity, which tends to make the body fall, and the resistance which the table offers to the fall. If the weight of the body exceed this resistance, equilibrium is destroyed, the table is broken, and the body falls.

31. **Centrifugal force.**—The force to which curvilinear motion, or motion in a circle, is due, is called *centrifugal force*. It may be explained as follows. Whenever a body has been put in motion in a particular direction, it tends, owing to its inertia, always to move in this direction. Hence, whenever a body is seen to move in a circle, this can only be due to some new force which deviates it. In fact, since a curved line may be considered to consist of a series of infinitely small straight lines, the moving body, owing to its inertia, always strives to follow the prolongation of the small straight line, or *tangent*, which it traverses at any given moment. It tends then to retain its motion in a straight line, and to fly from the curve which it is compelled to describe. This action is called the *centrifugal force*, from two Latin words which signify 'to fly from the centre.' Thus, when a stone in a sling is swung round and one end (fig. 17) is let go, the stone, being no longer held, flies off in a *tangential* direction.

It must, however, be observed that the term *centrifugal force*, though justified by usage, is not, strictly speaking, correct ; it is not a physical force, having a distinct existence of its own, but is a fictive one which conveniently designates the effect of the inertia of bodies ; indeed the effect is not properly centrifugal, since it consists in a motion tangential to the circle.

The production of centrifugal force in circular motion may be demonstrated by means of the apparatus represented in fig. 18. On a brass frame AB is stretched a stout brass wire, on which are slid two ivory balls which can move freely along the wire ; the balls being arranged as shown in the figure, the frame is rapidly rotated by means of the *turning-table*. The balls, projected by the centrifugal force, glide along the wire, and strike the ends with the greater force the greater the velocity of rotation.

32. **Effects of centrifugal force.**—The centrifugal force is greater the greater the velocity, and the more marked the curvature of the line along which the movable body passes. It is indeed proportional to the square of the velocity, and is inversely as the radius of the circle described. This is easily observed by swinging in a circle a ball attached to a string : the more rapid the velocity of rotation the greater is the pull on the hand. For this reason, railways should be as straight as possible, for, since the trains have a great velocity, the centrifugal force is continually tending to throw them off as they move along a curve, and the more so the sharper the curve. On railways where there are sharp curves the

outer rails are always higher than the inner ones. Skaters, too, in describing circles on ice, offer a resistance to centrifugal force by inclining the body inwards.

Owing to centrifugal force the mud which adheres to the wheels of a carriage moving along a muddy road is thrown off as soon as the centrifugal force is greater than that force which causes the mud to adhere to the rim. In a circus, the horses and their riders always incline their bodies towards the centre, and the greater the speed the greater their inclination. The object of this is to allow their weight to counteract the influence of the centrifugal force, which would throw them off if they stood upright.

Fig. 17.

In sugar-refineries, centrifugal force is applied in removing syrups from crystallised sugar. The sugar is placed in a cylindrical vessel made of wire gauze, which is put in rapid rotation. The centrifugal force scatters the coloured syrup through the meshes of the gauze, while the solid crystals are left behind colourless and pure. The same principle is applied in drying gun-cotton, and also in drying yarns in dye works and clothes in large laundries. A wet mop made to turn quickly about its own handle as an axis throws the water off on all sides, and quickly dries itself.

A hoop trundled along the ground may move for a long time before falling; but if we attempt to keep it upright while in a state of rest, it at once falls. The reason of this is that while in motion, if it inclines to one side, the inclination causes it to describe a curved line, whence arises a centrifugal force which opposes the fall of the hoop—at any rate, so long as it retains a sufficient velocity.

If a bucket containing water suspended by a cord is swung round with sufficient rapidity in a vertical circle, the water does not fall out even when the bottom is uppermost, for the centrifugal force is, in the conditions named, greater than gravity.

33. **Flattening of the earth at the poles.**—One of the most remarkable effects of centrifugal force is the flattening of the earth at the two poles. To explain this phenomenon we must premise that the earth, which is nearly spherical in form, rotates about an imaginary axis passing through its two poles, and that in

this rotation all points on the surface have not the same velocity, seeing that they do not describe the same paths in the same time. For, at the equator, they describe every twenty-four hours a circumference equal to that of the earth ; on the other hand, points taken at increasing distances from the equator gradually

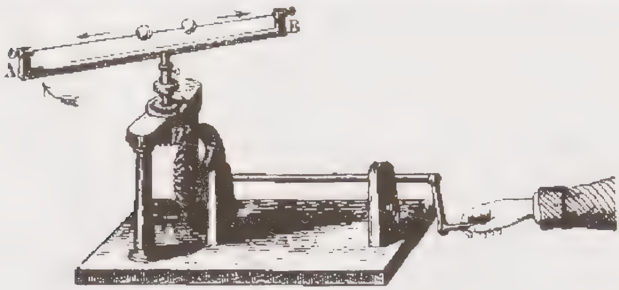


Fig. 18.

describe smaller and smaller circles, while points at the poles have no such motion. Hence, owing to the daily rotation about the earth's axis, a centrifugal force is produced which is greatest at the equator, and gradually diminishes up to the poles, where there is none at all. Owing to this inequality in the strength of the centrifugal force, there must arise an accumulation of matter about the equator, especially if, as geologists consider, the earth was originally in a state of fusion.

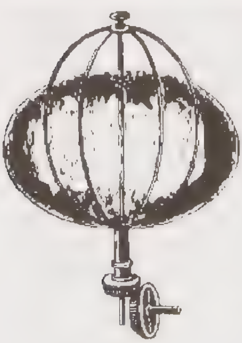


Fig. 19.

It has, in fact, been ascertained by direct determination (66) that the radius of the earth at the poles is less than that at the equator by about $\frac{1}{300}$ the latter, or $13\frac{1}{2}$ miles. A similar flattening has been observed in other planets.

To demonstrate this bulging at the equator and flattening at the poles, use is made of the apparatus represented in fig. 19. It consists of an iron rod, which may be fixed upon a turning-table instead of the piece AB (fig. 18). At the bottom of the rod are fixed four thin, elastic, metal strips, which are joined at the top to a ring which can slide up and down

the rod. The apparatus being then put in rapid rotation, the upper ring slides down the rod, to an extent depending on the rapidity of the rotation ; and if this is sufficiently rapid, the separate impressions of the individual strips coalesce into a single one which presents the appearance of a solid ellipsoidal figure.

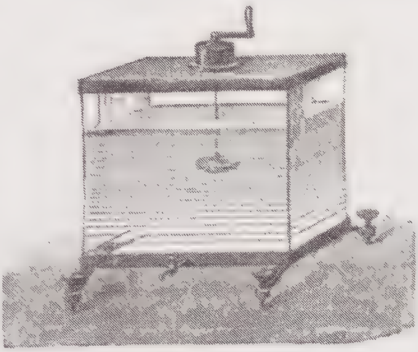
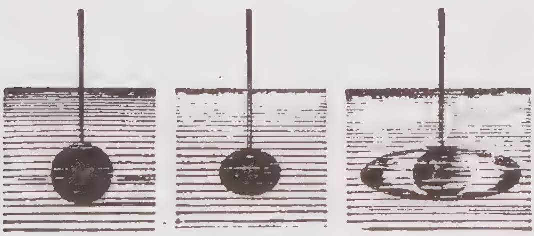


Fig. 20.

This flattening of the earth at the poles, and bulging at the equator, may also be easily illustrated with an actual liquid by means of an experiment of Plateau. The apparatus for this purpose consists of a cubical glass vessel, in the lid of which is a handle to which a rod is attached (fig. 20). The vessel contains dilute alcohol, and a small quantity of oil is introduced at the end of the rod by means of a suitable pipette. The oil is of the same specific gravity as the mass of liquid, and it forms a sphere which is quite stable (fig. 21, *a*).



a *b* *c*

Fig. 21.

If such a sphere is formed about the end of the wire, and this is turned, the oil is set in rotation, and the flattening is very marked (fig. 21, *b*). If the speed is increased, a mass of oil is detached and

forms about the central nucleus a concentric ring which suggests that of the planet Saturn (fig. 21, *c*).

LEVERS

34. **Mechanics. Machines.**—*Mechanics* is the science which treats of forces and of motion. Several forces being applied to the same body, it indicates the relation which must exist between them in order to produce equilibrium, or in order to produce a given effect.

Any apparatus which is used to transmit or direct the action of a force is a *machine*. When an apple is cut with a knife, the knife is the machine which transmits the force of the hand. The water-wheel and windmill are machines which utilise and direct the force of the watercourse and the wind respectively.

Machines cannot increase the energy of any source. The useful effect of a machine can never exceed that of the mechanical effort applied to it : whatever is apparently gained in power by a machine is lost in distance or in time. By modifying the action of the source of energy, however, a machine renders it capable of performing work which could not otherwise be done. For instance, by the aid of a lever, a man can raise weights which without such help would be quite impossible. By means of a crane a man can even raise a locomotive weighing as much as twenty tons. Machines are either simple or compound.

The simple machines are the lever, the wheel and axle, the pulley, the inclined plane, the wedge and the screw. All compound machines are modifications of these.

In reality there are only two essentially different machines—the lever and the inclined plane ; the wheel and axle and pulley are modifications of the former, while the screw and the wedge depend on the principle of the latter. We shall only describe here the lever, the simplest of all machines, and its modification, the wheel and axle. The balance, which is an example of the lever, will be treated later (50).

35. **Levers.**—A lever is a rigid bar of wood or of metal movable about a fixed point or edge, called the *fulcrum* ; and subject to the action of two forces which tend to move it in opposite directions. The applied force is called the *power*, and the other the *resistance*. Levers are divided into three classes, according to the different positions of the power and resistance in reference to the fulcrum.

A lever of the first kind is one in which the fulcrum is between the power and the resistance. Fig. 22 represents one of this kind, in which the power Q is exerted at B, the resistance P acts at A while C is the fulcrum.

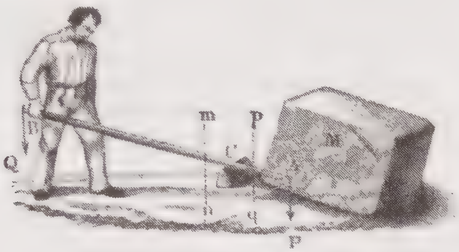


Fig. 22.

A lever of the second kind has the resistance between the power and the fulcrum, as in fig. 23.

A lever of the third kind is one in which the power is

Fig. 23.

applied between the resistance and the fulcrum, as represented in fig. 24.

In these different kinds of levers, the distances from the fulcrum to the power and to the resistance are called the *arms of the lever.* In fig. 22, for instance, the arm of the power is the

distance from C to B, and that from C to A is the arm of the resistance.

36. **Conditions of the equilibrium of levers.**—It may be shown that the effect produced by a force by means of a lever increases with the length of the arm upon which it acts: that is, if the arm is twice, thrice, or four times as long, the useful effect is two, three, or four times as great. This is what led Archimedes to say that, give him a fulcrum, and he would lift the world.

Since a force produces a greater effect the longer the arm of the lever, it follows that in order to produce equilibrium between

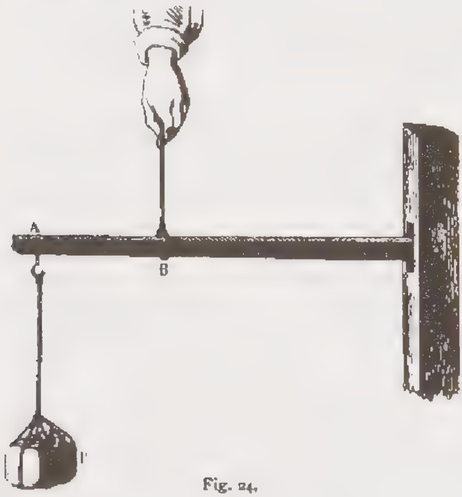


Fig. 24.

the power and the resistance, acting at the same time on a lever, if the arms are equal, *the two forces themselves must be equal*, and that if the arms of the lever are unequal, *the two forces must be inversely as the arms of the lever*; thus, if the power is one-third that of the resistance, the arm of the power should be three times as long as that of the resistance.

In a lever of the third kind the power must be always greater than the resistance, for the distance of the resistance P from the fulcrum AC (fig. 24) is always greater than the distance BC from the power B to the fulcrum. In a lever of the second kind the

power is always smaller than the resistance, for the arm BC is longer than the arm AC (fig. 23). These properties are expressed by saying that in a lever of the third kind there is a loss of power, and in one of the second kind a gain. In a lever of the first kind there may be either gain or loss, or they may just balance each other, for the arm BC of the power (fig. 22) must be either greater or less than, or equal to, the arm AC.

37. **Various applications of levers.**—Numerous applications of the different kinds of levers are met with in articles of everyday

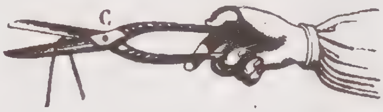


Fig. 25.

use. The ordinary balance (fig. 41) is a lever of the first kind, as is also a pump-handle. Scissors are another instance: each handle is a lever, the fulcrum of which is the pivot C; the power is applied by the hand, and the resistance is that offered by the material to be cut (fig. 25).

Among levers of the second class may be enumerated the oar of a rowing boat; the power is applied by the hands of the rower, the resistance is at the rowlock, while the fulcrum is situated at the end of the blade of the oar where it is in contact with the water. The knife fixed at one end, and used in slicing roots or cutting

Fig. 26.

bread, is a lever of the second kind. Nut-crackers (fig. 26) afford a third illustration, as also does the common wheelbarrow.

When two porters carry on a pole a load placed midway between them, they share it equally—that is, each bears half—for the pole becomes a lever, of which each porter is a fulcrum as regards the other; but if the load be nearer one than the other, he to whom it is nearer bears proportionally more of its weight.

The consideration of this kind of lever explains why a finger caught near the hinge of a shutting door is so severely crushed.

Fig. 27.

The third kind of lever is less frequently met with. The pedals used in grindstones are instances. In the latter case the pedal consists of a wooden board AC (fig. 27) forming a lever. The fulcrum is at C, on a bolt fixed to the frame; the power is the foot, B, of the man turning, and the resistance, which is the motion to be transmitted to the wheel, is applied at A by means of a rod joined to a crank in the centre of the stone.

In the common fire-tongs each leg is a lever of the third kind. The hand of a man pushing open a gate while standing near the hinges, moves through much less space than at the end of the gate, and must exert, therefore, a proportionally greater force. In some methods of determining the coefficient of expansion of a metal bar, the very small motion of the bar is multiplied by an arrangement of this kind.

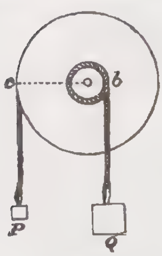


Fig. 28.

Numerous and most beautiful instances of levers are met with in the muscular system of men and animals, most motions of which are effected by levers of the third kind. Thus, in cracking a nut by the teeth the resistance is that offered by the nut, the fulcrum is the articulation of the jaw, while the muscle is the power.

The biceps muscle, by contracting to a very slight extent, can move the hand through a yard or more. A contraction of about

an inch of the muscles of the hip gives a man's step a length of four feet.

The *wheel* and *axle* (fig. 28) is an application of the lever. A rope to which the power P is applied passes round a groove in the circumference of the wheel, while another rope, which supports the weight Q, is coiled in the opposite direction round the axle. Thus the power is to the weight as the radius of the wheel is to that of the axle : that is, if the radius of the wheel is four times that of the axle the power can sustain four times its own weight.

CHAPTER IV

GRAVITATION

38. **Universal Attraction.**—It is stated that Newton, seeing an apple fall from a tree, was led by this circumstance to reflect upon the cause why bodies fell to the ground, and ultimately to the discovery of the important laws which govern the motion of the earth and of the stars.

They may be thus stated :—

1. *All bodies in nature exert a reciprocal attraction upon each other at all distances, in virtue of which they are continually tending towards each other.*

2. *For the same distance the attraction between bodies is proportional to their masses.*

3. *The masses being equal, the attraction varies with the distance, being inversely proportional to the square of their distances asunder.*

To illustrate this, we may take the case of two spheres, which attract each other just as if their masses were concentrated in their centres. If, without any other alteration, the mass of one sphere were doubled, trebled, etc., the attraction between them would be doubled, trebled, etc. If, however, the mass of one sphere being doubled that of the other were increased three times, the distance between their centres remaining the same, the attraction would be increased six times. If, finally, without altering their masses, the distance between their centres were *increased* from 1 to 2, 3, 4 . . . units, the attraction would be diminished to the 4th, 9th, 16th, . . . part of its original amount.

39. **Gravitation.**—The term *gravitation* is applied more especially to the attraction exerted between the heavenly bodies. The sun, being that member of our planetary system which has the largest mass, exerts also the greatest attraction, from which it might seem that the earth and the other planets ought to fall into the sun in consequence of this attraction. This would indeed be the case if they were only acted upon by the force of gravitation ; but,

owing to their inertia, the original impulse which they once received constantly tends to carry them away from the sun. The result is that the planets describe curves round the sun which are almost circular, their tendency to move along a straight line being constantly controlled by the attraction which the sun exerts upon them.

40. **Gravity.**—It is a matter of common observation that all bodies on the surface of the earth fall to the ground when not supported. This is what we mean by saying that bodies possess weight. The force in virtue of which bodies fall is called *gravity.* It is a *particular case* of universal attraction, and is due to the reciprocal attraction exerted between the earth and bodies placed on its surface; it acts equally upon all bodies, whether they are at rest or in motion—whether they are solids, liquids, or gases. Some bodies, such as clouds and smoke and balloons, appear not to be influenced by this force, for they rise in the atmosphere instead of sinking; yet this is no exception to the action of gravity, but is due to the fact that air possesses weight, and produces on bodies immersed in it a buoyancy which is sometimes equal to, and sometimes greater than, the effect of gravity.

Gravity, being a particular case of universal attraction, acts upon bodies proportionally to their mass and inversely as the square of their distance—that is, a body which contains twice or thrice as much matter as another is attracted by the earth with a twofold or threefold force, or, in other words, *weighs* twice or thrice as much. In like manner, if one and the same body could be moved to twice or thrice its present distance from the *centre* of the earth, it would have one-fourth or one-ninth of its present weight. We say the *centre*, and not the *surface*, of the earth; for it is demonstrated in treatises on mechanics that the attractive force of the earth which causes bodies to fall must be calculated from its centre, being the same as it would be if the whole mass of the earth were concentrated at its centre.

From the magnitude of the earth's radius, which is about 4,000 miles, all bodies on its surface may be considered to be virtually at the same distance from the centre, and we may therefore conclude that their difference in weight is merely due to their difference in mass.

41. **The weight of a body increases from the equator to the poles.**—The magnitude of the force which makes bodies fall is not exactly the same at all points of the earth's surface. Two causes make it increase from the equator to the poles: the daily rotation of the earth about its axis and the flattening at the poles. For the

rotation of the earth gives rise to a centrifugal force acting from the centre to the surface—that is, in the opposite direction to the force of gravity. Hence, bodies are continually acted upon by two forces in opposite directions : the force of gravity, which draws them towards the centre, and the centrifugal force, which tends to drive them away from it. So that it is really the excess of the first force over the second which makes bodies fall. But as the centrifugal force decreases from the equator towards the poles (33), the excess of gravity over this force becomes greater, and thus the weights of bodies increase as they come nearer the poles.

The flattening of the earth concurs in producing the same effect ; for, in consequence of it, bodies on the surface of the earth are at the poles 13½ miles nearer the centre than they are at the equator, and are therefore more attracted. It must be added that the increase in weight due to the joint effect of these two causes is very small—thus, a weight of 1,000 at the equator would be 1,003 in our latitude and 1,005 at the poles. It cannot be detected by ordinary balances, for gravity would act both on the weight and on the body to be weighed. A body suspended, however, to a delicate spring balance would indicate slightly different weights, according as it was nearer to or further from the poles, or according as it was at a greater vertical distance above the earth.

42. **Vertical and horizontal lines.**—At any point of the earth's surface the direction of gravity—that is, the line which a falling body describes—is called the *vertical* line. The vertical lines drawn

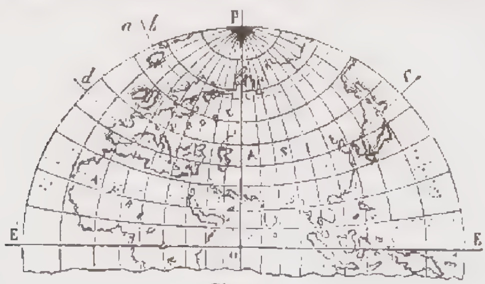


Fig. 29.

at different points of the earth's surface converge very nearly to the earth's centre. Hence, owing to the great distance from the surface of the earth to its centre, these verticals may be assumed to be parallel for points on the surface, *a* and *b* (fig. 29), not far

apart ; but they are less parallel the further apart the points, as shown by the verticals *a* and *d*. For points situated on the same meridian the angle contained between the vertical lines equals the difference between the *latitudes* of those points.

At each point on the surface of the earth, a man standing upright is in the direction of the vertical. But, as we have just seen, this direction changes from one place to another, and the same is the case with the position of the inhabitants of the various countries on the earth. As the earth is spherical, it follows that at two points exactly opposite, two men will be in inverted positions in reference to each other ; from which is derived the term *antipodes* (opposite as regards the feet) given to two diametrically opposite places or to the inhabitants of such.

A plane or a line is said to be *horizontal* when it is perpendicular to the direction of the vertical. The surface of water in a state of equilibrium is always horizontal. In speaking of the *level* (99) we shall learn how the horizontality of any surface or line is determined.

43. **Plumb-line.**—The vertical line at any point of the globe is generally determined by the *plumb-line* or *plummet* (fig. 30), which consists of a weight attached to the end of a flexible string. In obedience to the action of gravity, this weight draws the string in the direction of this force, and when it is at rest the string is in the vertical direction, which is that of a heavy body falling freely, and therefore of gravity. To ascertain by aid of the plumb-line whether a given surface—a wall, for example—is vertical, a small metal plate is used, the side of which is equal to the diameter of the weight. In the centre of this plate is a small hole, through which passes the string. Holding in one hand the plate and in the other the string, the edge of the plate is pressed against the wall : if the weight just touches it, the wall is vertical ; if the cylinder does not touch the wall, it shows that the wall is inclined inwards ; it is inclined outwards if the weight touches the wall when the plate is a little removed from it.

Fig. 30.

44. **Weight of a body.**—The *weight* of a body is the sum of the partial attractions which the earth exerts upon each of its molecules. We must again distinguish between the weight and the mass of a body (22). The latter is constant, while the weight depends

on the greater or less distance of the body from the earth. Thus, at a distance of four times the earth's radius from the centre, a ball which on the surface weighed a pound would only weigh an ounce, while if we conceive it fired in that position from a gun it would have the same penetrative power as if fired with the same velocity on the earth. The weight of a body must increase with its mass; that is, if it contains twice or thrice as much matter, its weight must be twice or thrice as great. The weight of a body is not to be confounded with *gravity*: this is the cause which produces the fall of bodies; the weight is only the effect. We shall presently see how weight is determined by means of the balance; the force of gravity is measured by the aid of the pendulum.

45. **Centre of gravity.**—We have seen that all the partial attractions which the earth exerts upon each of the molecules of a body are equivalent to a single force, which is the weight of a body. Now, it is shown in mechanics that, whatever be the shape of any body, there is always a certain point through which this single force, the weight, acts, in whatever position the body be placed in respect to the earth; this point is called *the centre of gravity* of the body.

To find the centre of gravity of a body is a purely geometrical problem; in many cases, however, it can be at once determined. For instance, the centre of gravity of a straight piece of wire is its middle point; in the case of a circular lamina and of a sphere it coincides with the geometrical centre; in cylindrical bars it is the middle point of the axis; in a square or a parallelogram it is at the point of intersection of the two diagonals. These rules, it must be remembered, presuppose that the several bodies are of uniform density.

46. **Experimental determination of the centre of gravity.**—The centre of gravity of a body may also be found by experiment: When its weight is not too great, it is suspended by the string in two different positions; the centre of gravity of the body is necessarily below the point of suspension, and therefore in the prolongation of the vertical cord which sustains it. If, then, in two different positions, the vertical lines of suspension be prolonged, they cut one another, and the point of intersection is the centre of gravity sought. The centre of gravity of a body is not necessarily in the mass of a body itself—thus, in a shell it would be in the centre of the hollow space.

In the case of thin, flat substances, like a piece of cardboard or

a sheet of tinplate, the centre of gravity may be found by balancing the body in two different positions on a horizontal edge; for instance, sliding them near the edge of a table until they are ready to turn in either direction (fig. 31). The centre of gravity is then on the line *ab*. Seeking, in a similar manner, a second position of equilibrium, in which the line of contact is *cd*, for instance, the centre of gravity must necessarily be on both these lines —that is, must be at the point of their intersection, *g*; or, more accurately, a little below this point, in the interior of the body, and an equal distance from its two faces.

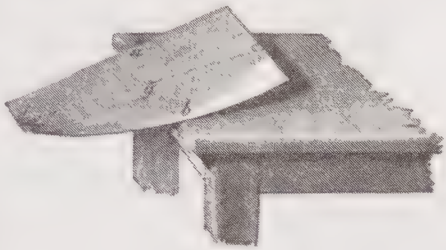


Fig. 31.

If the body be thicker, three positions of equilibrium must be found; the centre of gravity is then at the point of intersection of the three planes passing vertically through the lines of contact when the body is in equilibrium.

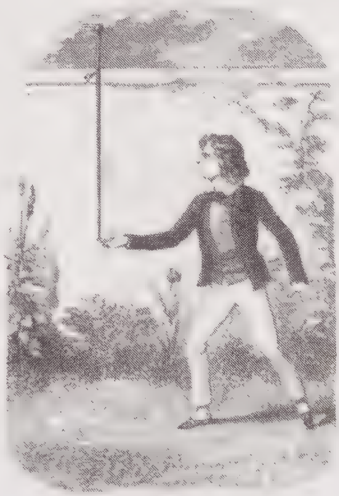


Fig. 32.

47. **Equilibrium of heavy bodies.**—As the centre of gravity is the point where the whole action of gravity is concentrated, it follows that whenever this point rests upon any support, the action of gravity is counterbalanced, and therefore the body remains in equilibrium. There are, however, several cases, according as the body has one or more points of support.

Where the body has only one point of support, equilibrium is

only possible when the centre of gravity either coincides with this point or is exactly above or below it in the same vertical line; for then the action of gravity is balanced by the resistance of the fixed point through which this force passes. The plumb-line (fig. 30) is a case of this kind, the centre of gravity being below the point of support. Another example is the case of a stick balanced on the finger, as seen in fig. 32, in which the letter *g* indicates the position of the centre of gravity exactly over the point of support. As soon as the stick is out of the vertical, its centre of gravity is lower, and the stick falls, if care be not taken to bring the point of support below the centre of gravity, by which equilibrium is restored. A long stick is more easily balanced than a short one, for the centre of gravity of the former has to fall through a greater distance, and there is more time to adjust the point of the support.

Fig. 33.

If the body has two points of support, it is not necessary for equilibrium that its centre of gravity coincide with either of these points, or be exactly above or below; it is sufficient if it be exactly below or above the right line which joins these two points, for the action of gravity may then be decomposed into two forces applied at the points of support, and destroyed by the resistance of these points. A man on *stilts* (fig. 33) is an example of this case of equilibrium.

Fig. 34.

Lastly, if a body rests on the ground by three or more points of support (fig. 34), equilibrium is produced whenever the centre of gravity is within the *base* formed

by these points of support ; that is, whenever the vertical let fall from the centre of gravity to the earth is within the points of support ; for gravity cannot then overturn the body beyond its points of support, and its only effect is to settle it more firmly on the ground.

48. **Different states of equilibrium.**—Although a body supported by a fixed point is in equilibrium whenever its centre of gravity is in the vertical line through that point, the fact that the centre of gravity is always tending to occupy the lowest possible position leads us to distinguish between three states of equilibrium—*stable, unstable, neutral.*

A body is said to be in *stable equilibrium* if it tends to return to its first position after the equilibrium has been slightly disturbed.

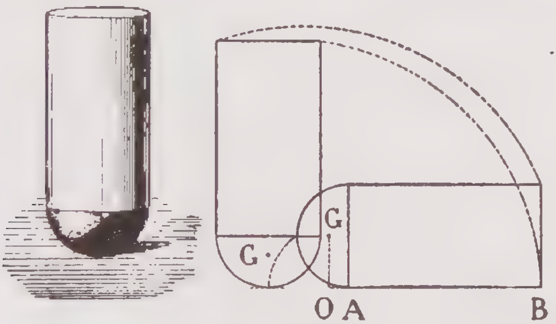


Fig. 35.

Every body is in this state when its position is such that the slightest alteration of the same elevates its centre of gravity ; for the centre of gravity will descend again when permitted, and after a few oscillations the body will return to its original position. The pendulum of a clock continually oscillates about its position of stable equilibrium.

An interesting illustrative experiment can be simply made by means of a cylinder of pith or of cork loaded at the bottom by half a lead bullet (fig. 35) ; if this is turned round, so as to become horizontal, the centre of gravity, G, being raised from its original position, quickly returns to it, making the cylinder again vertical.

A body is said to be in ***unstable equilibrium*** when, after the slightest disturbance, it tends to depart still more from its original position. A body is in this state when its centre of gravity is vertically above the point of support, or higher than it would be in any adjacent position of the body. An egg standing on its end, or a stick balanced upright on the finger, is in this state (fig. 32).

Another illustration is that of a disc of wood with a small mass of lead near the edge. If placed on a plane slightly inclined, so that the vertical from the centre of gravity, G (fig. 36), is a little in front of the point of contact, O, the disc will rise up the plane but will stop, and move down when the vertical passes through the point of contact, O_1. In reality the centre of gravity during the ascent has fallen from G to G_1.

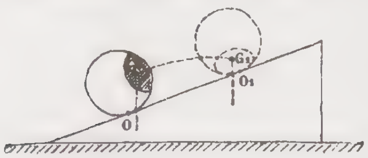


Fig. 36.

Neutral equilibrium.—A body is in a state of neutral equilibrium when it remains at rest in any position which may be given to it. This can only be the case when an alteration in the position of the body neither raises nor lowers its centre of gravity. A perfect sphere resting on a horizontal plane is in this state.

Fig. 37 represents three cones, A, B, C, placed respectively in stable, unstable, and neutral equilibrium upon a horizontal plane. The letter *g* in each shows the position of the centre of gravity.

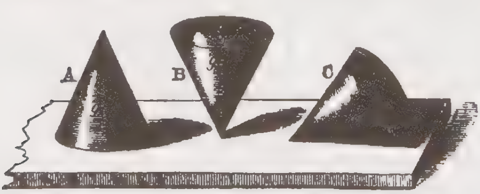


Fig. 37.

49. Examples of equilibrium.—It follows, from what has been said, that the wider the base on which a body rests, the greater is its stability, for then, even with a considerable inclination, a vertical line through its centre of gravity still falls within its base.

The well-known leaning towers of Pisa and Bologna are so much out of the vertical that they seem ready to fall at any moment; and yet they have remained for centuries in their present position, because the perpendiculars let fall from their centres of gravity are within the base. Fig. 38 represents the

tower of Bologna, built in the year 1112, and known as the *Garisende.* Its height is 165 feet, and it is 7 or 8 feet out of the vertical. The leaning is due to the foundations having given way. The tower on the side is that of Asinelli, the highest in Italy.

In the cases we have hitherto considered, the position of the centre of gravity is fixed; this is not the case with men and

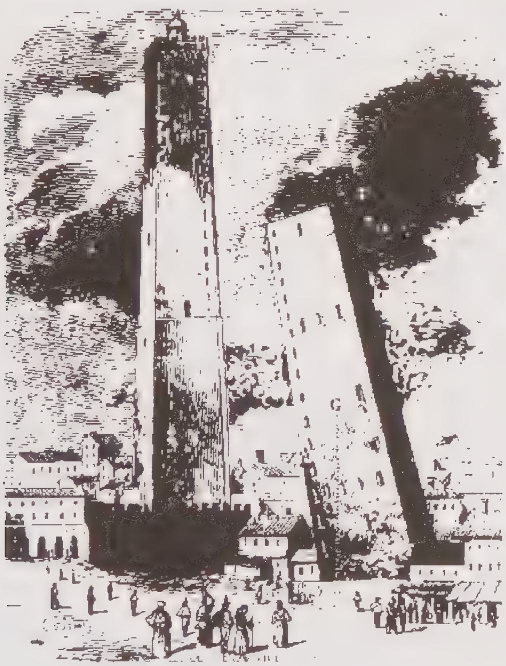


Fig. 38.

animals, whose centre of gravity is continually varying with their attitudes, and with the loads they support.

When a man, not carrying any load, stands upright, his centre of gravity is about the middle of the lower part of the pelvis—that is, between the two thigh-bones. This, however, is not the case with a man carrying a load; for, his own weight being added to

that of the load, the common centre of gravity is neither that of the man nor of his burden.

In this case, in order to retain his stability, the man must so modify his attitude as to keep his centre of gravity directly above the base formed by his two feet. Thus, a porter with a load on his back is obliged to lean forward (fig. 39); a stout person inclines somewhat backwards; while a man carrying a load in one hand is obliged to lean his body on the opposite side (fig. 40).

Again, it is impossible to stand on one leg if we keep one side of the foot and head close to a vertical wall, because the latter prevents us from throwing the body's centre of gravity vertically above the supporting base.

Fig. 39.

Fig. 40.

In the art of rope-dancing the difficulty consists in maintaining the centre of gravity exactly above the rope. In order more easily to accomplish this, the performer holds in his hands a long pole, which, as soon as he feels himself leaning on one side, he inclines towards the opposite one; and thus contrives to keep the centre of gravity common to himself and to the pole in a vertical line above the rope, and so preserves his equilibrium.

A broad waggon is more stable than a narrow one; and in loading a waggon, the heaviest goods should be in the bttoom of the waggon, so that the centre of gravity of the whole may be as low as possible.

A boat is more easily upset when it is loaded to a great height; or when a person stands up in it, than when he is seated.

The stability of a body is greater the greater the work required to overturn it, so that the pyramidal form is very stable; for the same dimensions, columns of wood are more easily upset than those of stone or of iron.

A quadruped stands firm when the centre of gravity of his entire body lies over and within the square which is formed on the ground by his feet. If a man raises his arm, the centre of gravity is displaced; if a bird stretches out its neck, its centre of gravity is moved forwards.

Men stand less firmly than quadrupeds; they learn to walk with greater difficulty, and in doing so must continually balance themselves, and with any loss of consciousness at once fall over.

50. **The balance.**—The balance is an instrument for determining the *relative* masses of bodies, and since in one and the same place the weights are proportional to the masses, it serves to determine the weights.

The ordinary balance (fig. 41) consists of a lever of the first kind, called the *beam*, AB, with its fulcrum in the middle; at the extremities of the beam are suspended two *scale-pans*, D and C; one intended to receive the object to be weighed, and the other the counterpoise. The fulcrum consists of a steel prism, *n*, commonly called a *knife-edge*, which passes through the beam, and rests with its sharp edge, or *axis of suspension*, upon two supports; these are formed of agate or of polished steel, in order to diminish the friction. A needle or pointer is fixed to the beam, and moves with it in front of a fixed, graduated arc; when the beam is perfectly horizontal, the needle points to the zero of the graduated arc.

Since two equal forces in a lever of the first kind cannot be in equilibrium unless their leverages are equal (36), the length of the arms *n*A and *n*B ought to remain equal during the process of weighing. To secure this, the scales are suspended from hooks, whose curved parts have sharp edges, and rest on similar edges at the ends of the beam. In this manner the scales are supported on what are practically mere lines, which remain unmoved during the oscillations of the beam. This mode of suspension is represented in fig. 41.

The weight of any body is determined by placing it in one of the pans of the balance—D, for instance—and adding weights to the other until equilibrium is established, which is the case when the beam is quite horizontal.

51. **Conditions to be satisfied by a good balance.**—A good

balance should be *accurate*—that is, it should give exactly the weight of a body ; it should also be *delicate*—that is, the beam should be inclined by a very small difference between the weights in the two scales.

Conditions of accuracy. i. *The two arms of the beam ought to be precisely equal;* otherwise, according to the principle of the lever 36), unequal weights will be required to produce equilibrium. To test whether the arms of the beam are equal, weights are placed in the two scales until the beam becomes horizontal ; the contents of

Fig. 41.

the scales being then interchanged, the beam will remain horizontal, as shown by the index, if its arms are equal, but if not, it will sink on the side of the longer arm.

ii. *The balance ought to be in equilibrium when the scales are empty;* for, otherwise, unequal weights must be placed in the scales in order to produce equilibrium. It must be borne in mind, however, that the arms are not necessarily equal, even if the beam remains horizontal when the scales are empty ; for this result might also be produced by giving to the longer arm the lighter scale.

iii. *The beam being horizontal, its centre of gravity ought to be in the same vertical line with the edge of the fulcrum, and a little below the latter;* for, if the centre of gravity coincided with this line, the resultant action on the beam would be null, and the beam would not oscillate. If the centre of gravity were above the edge of the fulcrum, the beam would be in unstable equilibrium; while, if it is below the fulcrum, the weight of the beam is continually tending to bring it back to the horizontal position as soon as it diverges from it, and the balance oscillates with regularity.

Conditions of delicacy. i. *The centre of gravity of the beam should be very near the knife-edge;* for then, when the beam is inclined, its weight, only acting upon a short arm of the lever, offers but little resistance to the excess of weight in one of the pans.

ii. *The beam should be light;* for the friction of the knife-edge upon the supports is smaller the less the pressure. In order more effectually to diminish friction, the edges from which the beam and scales are suspended are made as sharp as possible, and the supports on which they rest are of some very hard material, such as steel or agate.

iii. Lastly, *the longer the beam the more delicate is the balance;* because the difference in the weights in the pans then acts upon a longer arm of the lever. The balance is one of the most accurate and delicate of physical instruments.

For the finer chemical and physical operations—such, for example, as those used in determining the standards of weight and measure—balances of extreme delicacy are required. Instruments of this kind have been constructed which, for a weight of one kilogramme in each pan, will turn with an excess of a tenth of a milligramme—that is, will indicate a difference of a ten-millionth in the weight of the body.

52. **Method of double weighing.**—Notwithstanding the inaccuracy of a balance, the true weight of a body may always be determined by its means. The body to be weighed is placed in one scale, and shot or sand poured into the other until equilibrium is produced—an operation which is called taking the *tare*; the body is then replaced by known weights until equilibrium is re-established. The sum of these weights will necessarily be equal to the weight of the body, for, acting under precisely the same circumstances, both have produced precisely the same effect.

Or the body to be weighed is placed in the left pan, and

weights added to the right one until equilibrium is obtained; the body is next placed in the right pan and the weights in the left. If the weights in the two cases do not differ much, the true weight of the body is their arithmetic mean.

53. **The steelyard.**—This instrument is in principle a lever of the first kind (35). The fulcrum (fig. 42) is at C, and the load, P, is suspended at A, so that it acts on the short arm of the lever, AC. The longer arm, BC, is graduated into equal parts, and the weight, Q, with its ring-formed knife-edge, D, is moved along the sharp edge of this arm until a position is found in which

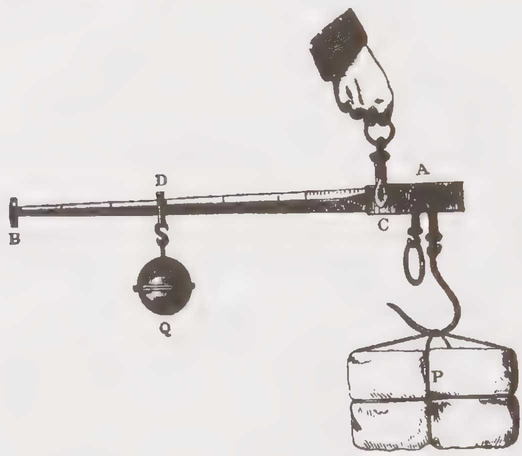


Fig. 42.

it just counterbalances the load. It follows from the principle of the lever that the smaller weight acting through the longer distance, BC, is equivalent to the greater weight acting through the shorter distance, AC. The weight of the lever itself is allowed for in the graduations on BC.

This instrument is also known as the *Roman balance*; it has no great sensitiveness: it should show a difference of $\frac{1}{500}$ of the load.

54. **Weighing machines.**—One of the forms of these instruments, which are of frequent use in railway-stations, coal-yards, etc., for weighing heavy loads, is represented in fig. 43. It consists

of a platform, A, on which the body to be weighed is placed, and to which an upright, B, is fixed; the whole rests on a frame, HE, by the following mode of suspension.

To the upright, E, are adapted two pieces of iron, which support a beam, LR, by the aid of a knife-edge, which traverses it at O. The two arms of the beam are unequal in length; one of them supports a scale, D, in which are placed the weights; the other arm of the beam has two rods, by which is suspended the movable part, AB. In order to relieve the knife-edge which supports the

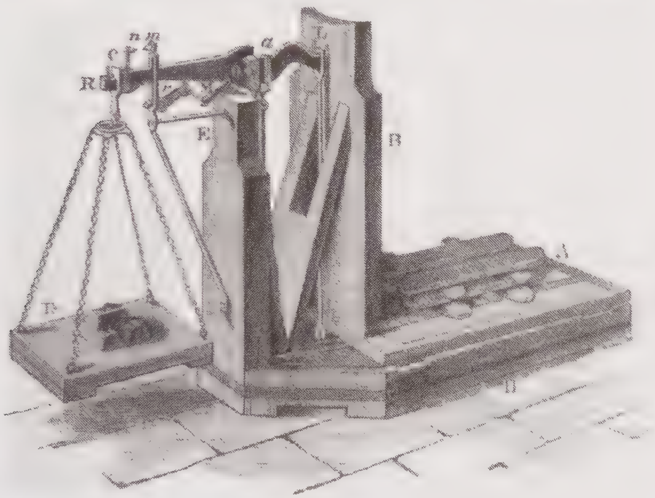


Fig. 43.

platform, and to avoid a shock when it is unloaded after a weighing has been made, the arm, OR, is lifted by raising a support, *r*, which is below the beam, by means of the handle, M. Two indicators, *m* and *n*, the first fixed to the frame and the second to the beam, show when the beam is horizontal.

To understand the working of the mechanism, reference must be made to fig. 44, in which the principal parts only are represented. A lever, *ih*, which bifurcates underneath the platform, rests at one end on a double knife-edge, *i*, and at the other on the lower end of the rod, L*h*, which is fixed to the beam. A second lever, *eg*, rests at *s* on the lever *ih*, attached at *g* to the rod *ag*,

which is also supported by the beam. Lastly, the distance *is* being the fifth of *ih*, *a*O is also a fifth of OL.

From this division of the two levers, *ih* and OL, into proportional parts, two important consequences follow. First, that, when the beam oscillates, the points *a* and *g* being lowered by a certain amount, the points L and *h* are lowered five times as much. But, for a similar reason, since the lever *ih* oscillates upon the knife-edge *i*, the knife-edge *s* is lowered one-fifth as much as the point *h*, and therefore just as much as *g*. The lever *eg*, therefore, descends parallel to itself, and therefore also the platform A.

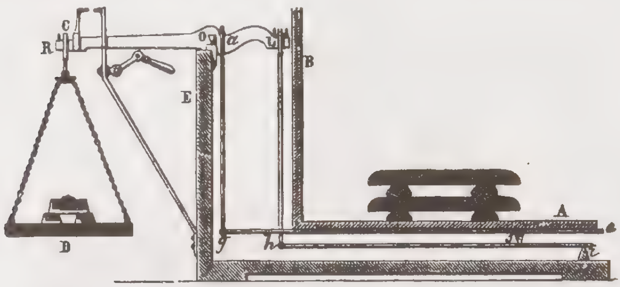


Fig. 44.

Secondly, it follows, from the proportional division of the levers OL and *ih*, that the pressure at the point of suspension, exercised by the load on the platform, is independent of the place which it occupies on the latter, so that it just acts as if it were applied along the rod *ag*. This may be deduced from the properties of the lever by a simple calculation, which cannot, however, be given here.

Lastly, since the weight is applied at *a*, the longer the arm of the lever OC as compared with O*a*, the smaller need be the weight in the scale D in order to produce equilibrium. In most weighing machines O*a* is the tenth of OC. Hence the weights in the scale D represent one-tenth the weight of the body on the platform.

CHAPTER V

LAWS OF FALLING BODIES. INCLINED PLANE. THE PENDULUM

55. **Laws of falling bodies.**—When bodies fall in a vacuum—that is, when they experience no resistance—their fall is subject to the following laws :—

I. *In a vacuum all bodies fall with equal rapidity.*

II. *The space traversed by a falling body in a given time is proportional to the square of that time*—that is, that if the space traversed in a second is 16 feet, in two seconds it will be 64 feet—that is, four times as much—and in three seconds nine times as much, or 144 feet, and so on.

III. *The velocity acquired by a falling body is proportional to the duration of its fall*—that is, that if the velocity at the end of a second is 32 feet per second, at the end of two seconds it is twice 32, or 64, at the end of three seconds 96 feet per second, and so forth.

To demonstrate the first law by experiment, a glass tube about two yards long (fig. 45) may be taken, having one of its ends completely closed and a brass stop-cock fixed to the other. After having introduced bodies of different weights and densities (pieces of lead, paper, feather, etc.) into the tube, the air is withdrawn from it by an air-pump, and the stop-cock closed. If the tube be now suddenly turned upside down, all the bodies will fall equally quickly. On introducing a little air, and again inverting the tube, the lighter bodies become slightly retarded, and this retardation increases with the quantity of air introduced.

It is, therefore, concluded that terrestrial attraction, which is the cause to which the fall of bodies is due, is equally exerted on all substances, and that the difference in the velocity with which bodies fall is occasioned by the resistance of the air, which is more perceptible the smaller the mass of bodies and the greater the surface they present.

The Staubbach, in Switzerland, is a good illustration of the

resistance opposed by the air to falling bodies : an immense mass of water is seen falling over a high precipice, but before reaching the bottom it is shattered by the air into the finest mist. In a vacuum, however, liquids fall like solids.

The *water-hammer* (fig. 46) illustrates this : the instrument consists of a thick glass tube about a foot long, half filled with water, the air having been expelled by ebullition previous to closing one extremity with the blowpipe. When such a tube is suddenly inverted, the water falls in one undivided mass against

Fig. 45.

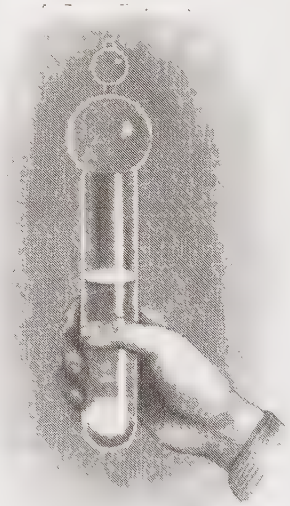


Fig. 46.

the other extremity of the tube, and produces a sharp, dry sound, resembling that which accompanies the shock of two solid bodies.

The slowness with which feathers and soap-bubbles fall is a further illustration of the resistance of the air.

The other laws of falling bodies are verified by the aid of the inclined plane (fig. 48) and of Atwood's machine (figs. 49–57).

56. **Inclined plane.**—Any plane surface more or less oblique in reference to the horizon is an *inclined plane*; such is that of an ordinary desk and of most roads.

When a body rests on a horizontal plane, the action of gravity is entirely counteracted by the resistance of this plane. This, however, is not the case when it is placed upon an inclined plane.

To understand this, let BAC (fig. 47) represent the principal section of an inclined plane, BC being the *height* and BA the *length* of the plane; the ratio of the height to the length is called the *sine* of the inclination, that is, of the angle BAC.

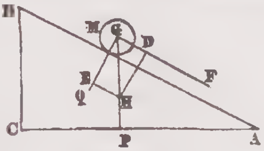


Fig. 47.

Let M be a body, which we will assume is spherical, resting on such a plane. Its weight P may be resolved into two forces (27), one, Q, perpendicular and the other, F, parallel to the inclined plane; the only effect of the former is to press it against the plane without imparting to it any motion, while that of F is to make the body move down the plane.

To arrive at the value of F, let a line GH be drawn which represents the weight of the body. Complete the parallelogram DGEH; the force F is then represented by the line GD. Then, since the triangles DGH and ABC are similar, as having equal angles, it follows that $F : P = BC : BA$; that is, that the ratio of the force tending to move the body along the plane is to the whole weight as the height of the plane is to its length; that is, is equal to the sine of the angle BAC, so that by diminishing the height of the plane we can make the body descend as slowly as we wish.

The principle of the inclined plane is made use of in rolling heavy casks into or out of a waggon by means of two strong beams connected by iron ties.

A horse drawing a carriage on a road where there is a rise of one in twenty is really lifting one-twentieth of the load, besides overcoming the friction of the carriage against the ground (23). Hence the importance of making roads as level as possible. For this reason a road up a very steep hill is made to wind or zigzag

all the way; and an intelligent driver, in ascending a steep hill on which is a broad road, usually winds from side to side.

57. **Demonstration of the second law of falling bodies by the inclined plane.**—Galileo's experiment. When bodies fall freely, the rate at which they do so is so great that the motion could not be followed. Galileo was the first to establish the laws of falling bodies by using the inclined plane to slacken or dilute the motion of a falling body so as to render it easily observable without destroying its nature. He constructed a groove by fixing two stout strips of wood about twenty feet in length parallel to each other with a narrow gap between them: the edges of the groove thus formed were made as smooth as possible, so as to diminish friction, and the falling body was a polished bronze ball. By raising one end the plane could be inclined at any angle.

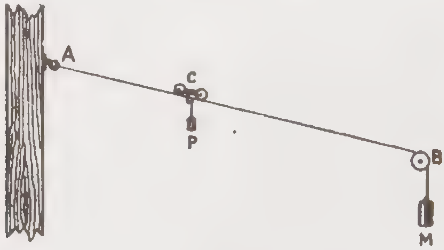


Fig. 48.

By noting the times required for a body to fall along the plane he arrived at the result that if the times are as 1 : 2 : 3 the corresponding distances are as 1 : 4 : 9; that is to say, that *the space traversed by a falling body is proportional to the square of the time during which it has been falling.*

A simple modification of Galileo's experiment is made by fixing (fig. 48) a long wire to a vertical support, its free end passing over a pulley which can be adjusted at any height; the wire is stretched by the weight M.

The moving body consists of two grooved wheels suitably connected, and to it is suspended the weight P.

By varying the position of the pulley the inclination of the wire is varied, and in addition to demonstrating the second law it is easy to show that the accelerating force is proportional to the sine of the inclination of the wire.

58. **Atwood's machine.**—The most exact method of establishing the laws of falling bodies is by means of a machine devised by Atwood, a Cambridge professor. The principle of the machine is as follows: A string passes over a fixed pulley and carries a weight at each end. If the weights are equal, say each one pound, there will be equilibrium, since each weight is balanced by the other. But when an extra weight, say one ounce, is added to one side, motion ensues, the moving force being the weight of one ounce, and the mass moved being the masses at the two ends of the string, in all 33 ounces. Thus, Atwood's machine is a contrivance by which we may cause a small force to act upon a large mass, and thus ensure the motion being as slow as we like. If P represent the moving force, m the mass acted upon, and a the acceleration produced, we have (22) the relation $P = ma$.

A convenient form of Atwood's machine is described in what follows. It consists of a wooden pillar about 2½ yards high (fig. 57). On the front of the pillar is a clockwork motion, H, regulated in the usual way by a seconds pendulum, P. On the right of the column is a graduated scale which measures the spaces traversed by the falling bodies. Along this scale two sliders move, which can be fixed by screws in any position; one of these has a disc, A, and the other a ring, B (fig. 53). At the top of the column is a brass pulley, R, whose axis, instead of resting on pivots, turns on the crossed edges of four other wheels, r, r, r', r', called *friction wheels*, since they serve to diminish friction. Two exactly equal weights, K and K′ (fig. 57), are attached to the end of a fine silk thread which passes round the pulley.

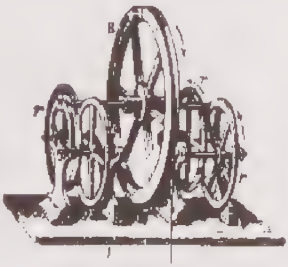


Fig. 49.

At the top of the column is a plate, n, on which is placed the falling body (fig. 50). This plate is fixed to a horizontal axis which carries a small catch, i, supported, when the plate is horizontal, by a lever, ab, movable in the middle. A spring placed behind the dial tends to keep this lever in the position represented in fig. 50, while an eccentric, e, moved by the clockwork, tends to incline towards the right the upper arm of the lever ab. The parts are so arranged that when the clock-hand is at zero of the graduation, the

lever *ab* is moved by the eccentric ; the plate *n* then lets fall the body which it sustained (fig. 51).

First experiment.—A weight K is placed upon the ledge *n* (fig. 50), and it is loaded with an over-weight, which consists of a brass strip, *m* (fig. 55), open at the side so as to let pass a rod fixed to the weight K. Then below the ledge *n* the slider A is placed at such a distance that K*m* requires a second to traverse the space *n*A, which is easily obtained after a few trials. If the mass *m* fell alone, its own weight would be the force acting upon it, and it would traverse about 16 feet in a second ; but, under the conditions of the experiment, the weight of *m* is the force acting upon the whole mass moved, viz. $m + K + K'$; and hence its fall is the more diminished, the smaller the mass *m* as compared with the sum of the masses K and K′.

The experiment being prepared as represented in fig. 50, the pendulum is made to oscillate ; the clockwork then begins to move, and when the needle arrives at zero, the plate *n* drops, the weights K and *m* fall too, and the space *n*A is traversed in a second by a uniformly accelerated motion. The experiment is recommenced, the slider A being placed at four times its original distance —that is, that if the distance A*n* were 8 inches (fig. 51), it is now 32 inches (fig. 52). But here, when the plate *n* drops, it is found that the weight K*m* requires exactly two seconds to traverse the space A*n*. Increasing the space traversed to 72 inches, the time required for the purpose is found to be three seconds. That is, that when the times are twice or thrice as great, the spaces traversed are four or nine times as great.

Hence *the distances traversed by a body falling freely under the action of gravity are proportional to the squares of the times.*

Second experiment.—To verify the law connecting the rate of fall with the time, the experiment is arranged as shown in figs. 53, 54, and 55 ; that is, the weights K and *m* being arranged as in the first experiment on the ledge *n*, the sliding ring B is placed at a distance of 8 inches below this, and the disc A at 16 inches below B. When the ledge *n* has dropped, the weights K and *m* still require a second to fall from *n* to B. But then the over-weight *m* being arrested by the ring B (fig. 54), the weight K only falls in virtue of its acquired velocity. The motion which was uniformly accelerated from *o* to B (19) is kept uniform from B to A ; for the weight, *m*, was the cause of the acceleration, and this having ceased to act, the acceleration ceases. It is then found that the space *o*B, equal

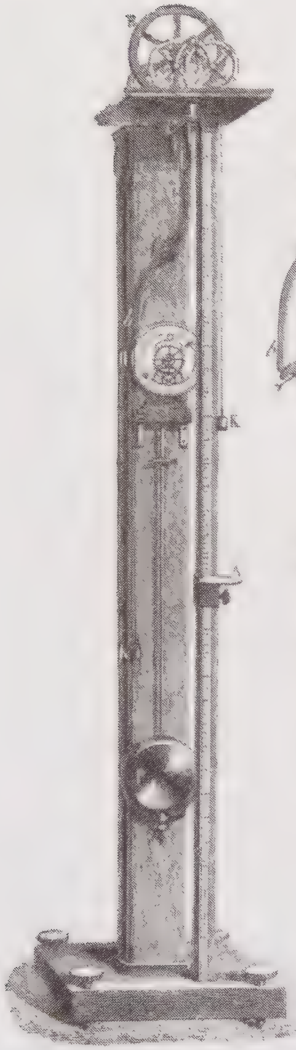


Fig. 57.

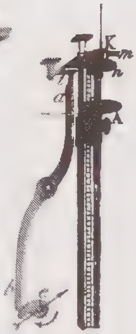


Fig. 50.

Fig. 51.

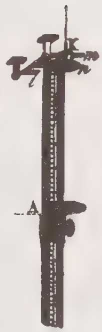


Fig. 52.

Fig. 53.

Fig. 54.

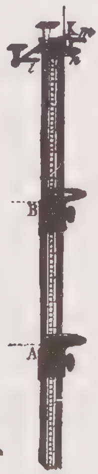


Fig. 56.

Fig. 55.

to 8, having been traversed in one second, the space BA, equal to 16, is also traversed in a second. That is, 16 represents the velocity of the uniform motion, which, starting from the point B, has succeeded to the uniformly accelerated motion.

The experiment is finally recommenced by placing the sliding ring B at the distance 32 (fig. 56), and the sliding disc A at the distance 32 below B. The space *o*B being then four times as great as in fig. 54, the weights K and *m* require, in accordance with the second law, twice the time. But the mass *m* being again arrested by the slider B, it is found that the weight K falls alone and uniformly from B to A in one second. The number 32 from B to A represents, then, the velocity acquired after two seconds of fall. In the first part of the experiment it was ascertained that the velocity acquired after one second was 16; hence, in double the time, the velocity acquired is double. It may be shown, in like manner, that after three times the time the velocity is trebled, and so on, thus proving the third law.

The algebraical expressions for the free fall of bodies are $v = gt$ (1) and $s = \frac{gt^2}{2}$ (2), where g is the acceleration of gravity, t the time, and s the space fallen through. By simple transformation we get from these two equations a third equation, $v^2 = 2gs$ (3).

We may also by Atwood's machine verify the formula $P = ma$, when m is kept constant: that is, prove that the moving force acting upon a given mass is directly proportional to the acceleration produced. To do this, all that is necessary is to move weights from the lighter to the heavier side of the string, thus keeping the mass set in motion, viz. the sum of the masses at the ends of the string, the same, while the moving force, which is the weight of the difference between them, is gradually increased. The acceleration is determined after each alteration.

59. **Morin's apparatus.**—The principle of this apparatus (fig. 58) is to make the falling body trace its own path. It consists of a wooden framework, about 7 feet high, which holds in a vertical position a very light wooden cylinder, M, which can turn freely about its axis. This cylinder is coated with paper divided into squares by equidistant horizontal and vertical lines. The latter measure the path traversed by the body falling along the cylinder, while the horizontal lines are intended to divide the duration of the fall into equal parts.

The falling body is a mass of iron, P, provided with a pencil

which is pressed against the paper by a small spring. The iron is guided in its fall by two light iron wires which pass through guide-holes on the two sides. The top of this mass is provided with a tipper which catches against the end of a bent lever, AC. This being pulled by the string K attached at A, the weight falls. If the cylinder M were fixed, the pencil would trace a straight line on it; but if the cylinder moves uniformly, the pencil traces the line *mn*, from which the law of the fall may be deduced.

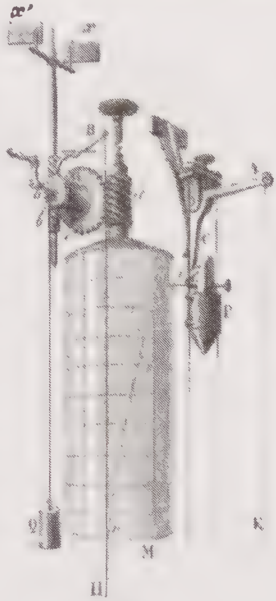


Fig. 58.

The cylinder is rotated by means of a weight, Q, suspended to a cord which passes round the axle G. At one end of this is a toothed wheel, *c*, which turns two endless screws, *a* and *b*, one of which is connected to the axis of the cylinder, and the other to two vanes, x and x'. At the other end of the axle is a ratchet wheel, *o*, it which fits the end of a lever, B; by pulling a cord fixed to the other end of B, the wheel is liberated, the weight Q descends, and the whole system begins to turn. The motion is at first accelerated, but as the air offers a resistance to the vanes (23), which increases as the rotation becomes more rapid, the resistance finally equals the acceleration which gravity tends to impart. From this time the motion becomes uniform. This is the case when the weight Q has traversed about three-quarters of its course; at this moment the weight P is detached by pulling the cord K, and the pencil then traces the curve *mn*.

If, by means of this curve, we examine the double motion of the pencil on the small squares which divide the paper, we see that, for displacements 1, 2, 3 . . . in a horizontal direction, the displacements are, 1, 4, 9 . . . in a vertical direction. This shows that the paths traversed in the direction of the fall are directly as the squares of the lines in the direction of the rotation, which verifies the second law of falling bodies.

From the relation which exists between the two dimensions ot the curve *mn*, it follows that this curve is a *parabola*.

60. **Pendulum.**—This name is given to any heavy mass suspended by a thread to a fixed point, or to any metal rod movable about a horizontal axis. The ball, *m*, suspended by the thread, *cm*, which is fixed at the top at *c* (fig. 59), is a pendulum.

So long as the thread is vertical, which is the case when the centre of gravity of the ball is exactly below the point of suspension, *c*, the pendulum remains at rest, for the action of gravity is balanced by the resistance at this point. This is no longer the case

Fig. 59.

Fig. 60.

Fig. 61.

when the pendulum is removed from its vertical position ; when it is placed, for instance, in the direction *cn* (fig. 60). The ball being raised, gravity tends to make it fall ; it returns from *n* to *m*, and reaches the latter point with exactly the velocity it would have acquired by falling vertically through the height *om*. The ball, accordingly, does not stop at *m*, but, in virtue of its inertia, and of its acquired velocity, it continues to move in the direction *mp*. As the ball rises, however, gravity, which had acted from *n* to *m* as an accelerating force, now exerts a retarding action, for it acts in a direction contrary to that of the motion ; the motion, accordingly, becomes slower, and the ball stops at a distance, *mp*, which would

be exactly equal to *mn*, were it not for the resistance of the air and also the rigidity of the thread, *cm*, which, as it is, offers a certain resistance to being bent about the point *c*, in passing from the position *cn* to *cp*, and *vice versa*.

This being premised, the moment the ball stops at *p* gravity, acting so as to make it fall again, brings it from *p* to *m*, when, owing to the velocity acquired in the fall, it rises in effect as far as *n*, and so on. A backward and a forward motion is thus produced from *n* towards *p*, and from *p* towards *n*, which may last several hours.

This motion is described as an *oscillating motion*. The path of the ball from *n* to *p*, or from *p* to *n*, is known as a *semi-oscillation*, a *complete oscillation* being the motion from *n* to *p*, *and* from *p* to *n*. In France the former is known as a *single* oscillation, and the backward and forward motion as a *double* oscillation.

The time of a complete oscillation is called the *period* of the pendulum.

The extent or *amplitude* of the oscillation is the distance between the extreme and mean positions, *cn* and *cm*, and is measured by the arc, *mn*.

61. **Simple and compound pendulum.**—A distinction is made in physics between the *simple* and the *compound* pendulum. A *simple* pendulum would be that formed by a *single* material point, suspended by a thread *without* weight. Such a pendulum has merely a theoretic existence; and it has only been assumed in order to arrive at the laws of the oscillations of the pendulum, which we shall presently describe.

A *compound* or *physical pendulum* may be defined to be any body which can oscillate about a point or an axis. The pendulum described above (fig. 59) is of this kind. The form may be greatly varied, but the most ordinary one is a steel or wooden rod (fig. 63) fixed at the top to a thin, flexible steel plate, or to a knife-edge like that of the balance (fig. 41). At the bottom of the rod is a heavy, lens-shaped mass of metal, usually of brass, and known as the *bob*. The lens shape is preferred to the spherical form, for, for the same mass, it presents less resistance to the air.

62. **Laws of the simple pendulum. Galileo.**—Whatever be the form of the pendulum, its oscillations are always expressed by the following laws. The law that one and the same pendulum makes its oscillations in equal times was discovered by Galileo, the celebrated physicist and astronomer at the end of the sixteenth century. It

is related that he was led to this discovery, while still young, by observing the regular motion of a lamp suspended to the vault of the cathedral at Pisa. This property of the pendulum has received the name of *isochronism*, from two Greek words which mean equal times, and such oscillations are said to be *isochronous*.

First law, or law of isochronism.—*The oscillations of one and the same pendulum are isochronous—that is, are effected in equal times.* This law is only perfectly exact when the oscillations are of small amplitude, four or five degrees at most; for a greater amplitude the oscillation is longer.

Second law, or law of lengths.—With pendulums of different lengths *the durations of the oscillations are proportional to the square roots of the lengths of the pendulums*—that is to say, that if the lengths of the pendulums are as 1, 4, 9, 16, the times of oscillations will be as 1, 2, 3, 4; these being the square roots of the former set of numbers.

A simple pendulum 9·76 inches in length makes an oscillation (to *or* fro motion) in half a second; while one 156 inches long requires two seconds to make a single oscillation.

Third law.—If the length of the pendulum remains the same, but the substances are different, the *duration of the oscillations is independent of the substance of which the pendulums are formed*—that is, that whether of wood, or of ivory, or of any kind of metal, they all oscillate in the same time.

Fourth law.—*The time of an oscillation of a given pendulum is inversely as the square root of the force of gravity in the place in which the observation is made.*

These laws are summed up in the formula $t = 2\pi\sqrt{\frac{l}{g}}$, where t = the time of a complete oscillation, l = the length of the pendulum, and g = the acceleration of gravity.

63. **Demonstration of the laws of the pendulum.**—In order to demonstrate the laws of the simple pendulum we are compelled to employ a compound one the construction of which differs as little as possible from that of the simple one (61). For this purpose a small sphere of a very dense substance, such as lead or platinum, is suspended from a fixed point by means of a fine wire. A pendulum thus formed oscillates almost like a simple pendulum the length of which is equal to the distance of the centre of the sphere from the point of suspension.

In order to verify the isochronism of small oscillations, it is

merely necessary to count the number of oscillations made in equal times, as the amplitudes of these oscillations diminish from *pn* to *rq* (fig. 61), say from three degrees to a fraction of a degree; this number is found to be constant.

It is also necessary to take into account the resistance of the air; this is done either by making the experiments in a vacuum or by introducing a numerical correction for the purpose.

That the times of oscillation are proportional to the square roots of the lengths is verified by causing pendulums whose lengths are as the numbers 1, 4, 9, . . . to oscillate simultaneously (AB, fig. 62). The corresponding numbers of oscillations in a given time are then found to be proportional to the fractions 1, $\frac{1}{2}$, $\frac{1}{3}$, etc. . . . which shows that the times of oscillation increase as the numbers 1, 2, 3, . . . etc.

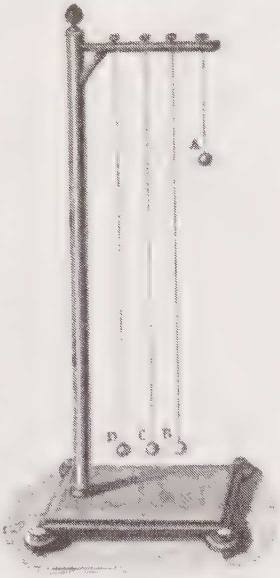


Fig. 62.

By taking several pendulums of exactly equal lengths, B, C, D (fig. 62), but with spheres of different substances, lead, copper, ivory, it is found that, neglecting the resistance of the air, these pendulums oscillate in equal times, thus showing that the accelerating effect of gravity on all bodies is the same at the same place.

64. **Measurement of the force of gravity.**—The relation which the fourth law of the pendulum establishes between the number of oscillations in a given time and the force of gravity is used to determine the magnitude of this force at different places on the globe. By counting the number of oscillations which one and the same pendulum makes in a given time—a minute, for example—in proceeding from the equator towards the poles, it has been found that this number continually increases, proving, therefore, that the force of gravity increases from the equator towards the poles.

The value of the acceleration of gravity (g) at any place is determined from the formula $t = 2\pi\sqrt{\frac{l}{g}}$, by observation of t and l. If

t is expressed in seconds and l in feet, g is found to be in London 32·19; that is, when a body falls freely under the action of gravity —the resistance of the air being either eliminated or allowed for—it gains a velocity of 32·19 feet per second in each second of its fall. This is expressed by saying that $g = 32{\cdot}19$ feet per second per second.

Fig. 63.

The pendulum method is the most accurate method of determining this important physical constant.

Since the velocity which a force imparts to a movable body in a given time is greater in proportion as the force is greater, the force of gravity in different places is measured by the velocity which it imparts to a body falling freely in a vacuum: while at London, as we have seen, its value is 32·19, at Paris it is 32·18, Madrid 32·15, at New York it is 32·16, at the equator it is 32·09, and at Spitzbergen 32·25.

65. **Application of the pendulum to clocks.**—The regulation of the motion of clocks is effected by means of pendulums, that of watches by balance-springs. Pendulums were first applied to this purpose by Huygens in 1658, and in the same year Hooke applied a spiral spring to the balance of a watch. The manner of employing the pendulum is shown in fig. 63. The pendulum-rod passing between the prongs of a fork, *a*, communicates its motion to a rod, *b*, which oscillates on a horizontal axis, *o*. To this axis is fixed a piece, *mn*, called an *escapement* or *crutch*, terminated by two projections or *pallets* which work alternately with the teeth of the *escapement-wheel*, R. This wheel being acted on by the weight tends to move continuously, let us say in the direction indicated by the arrowhead. Now, if the pendulum is at rest, the wheel is held at rest by the pallet, *m*, and with it the whole of the clockwork and the weight. If, however, the pendulum moves and takes the position shown by the dotted line, the pallet, *m*, is raised, the wheel *escapes* from the confinement in which it was held by the pallet, the weight descends, and causes the wheel to turn until its motion is

arrested by the other pallet, *n*; which, in consequence of the motion of the pendulum, will be brought into contact with another tooth of the escapement-wheel. In this manner the descent of the weight is alternately permitted and arrested—or, in a word, *regulated*—by the pendulum. By means of a proper train of wheelwork the motion of the escapement is communicated to the hands of a clock; and consequently their motion, too, is regulated by the pendulum.

Hence, to regulate a clock when it goes too slow or too fast, the length of the pendulum must be altered. If the clock goes too slow, it is because the pendulum oscillates too slowly, and the latter must therefore be shortened: if, on the contrary, it goes too fast, the pendulum must be lengthened. This shortening or lengthening is usually effected at the top of the pendulum by varying the length of the oscillating portion of the steel strip by which it is suspended. Clocks are provided with a simple arrangement for this purpose, which, however, is not represented in the figure.

A pendulum which makes one (single) oscillation in a second is called a *seconds pendulum*. The period (60) of a seconds pendulum is two seconds. The length of a seconds pendulum is not the same in different parts of the earth; it is somewhat less at the equator than at the poles. In London it amounts, approximately, to 39·14 inches; at Hammerfest to 39·19; at Paris to 39·13; at New York and at Milan to 39·10 inches; at the equator to 39·02 inches; and at the Cape of Good Hope to 39·08 inches. The average length, 39·11 inches, is very near that of the metre, which is 39·37 inches.

Since heat expands bodies, the length of the pendulum will be greater in summer and less in winter. Hence a clock which has been once regulated for the mean annual temperature will lose in summer and will gain in winter. How this effect of temperature is counteracted by a self-acting arrangement will be seen in the chapter on Heat.

66. **Determination of the figure of the earth.**—Richer, a French astronomer, found in 1671, in a journey from Paris to Cayenne, which is near the equator, that a clock which kept correct time in Paris went more slowly in Cayenne. It lost as much as 2½ minutes in a day, an amount greater than could have been due to the lengthening of the pendulum owing to the action of heat; and in order to regulate the clock it was necessary to shorten the pendulum by about the $\frac{1}{10}$th of an inch. The converse phenomenon was also observed, that the pendulum which had been regulated to

beat seconds at Cayenne went too fast at Paris, and had to be lengthened to a corresponding extent.

The true cause of this phenomenon was first pointed out by Newton, who ascribed it to the fact that the earth was not a perfect sphere ; for if it were, then, on every part of the earth's surface, one and the same pendulum would be at the same distance from the centre of gravity and would oscillate everywhere at the same rate. The fact that in some places it oscillates more slowly than in others is a proof that in the former the pendulum is less acted on by gravity than in the latter—that is, it is a greater distance from the centre of the earth.

Subsequent very accurate measurements have established the fact that the force of gravity does diminish from the equator to the poles—that is, the surface of the earth at the poles is nearer the centre than at the equator, or that the earth is somewhat flattened at the poles (41).

67. **Metronome.**—This is another application of the isochronism of the oscillations of the pendulum, and is used to mark the time in practising music. As the time varies in different compositions, it is important to be able to vary the duration of the oscillations, which is effected as follows. The bob of the pendulum, B (fig. 64), is of lead, and it oscillates about an axis, *o* ; the rod, which is prolonged above this axis, is provided with a weight, A, which slides on this rod and can be fixed in any position. This weight obviously acts in opposition to the oscillations of the bob, B ; for when this tends to oscillate, for instance, from right to left, the weight tends to move the rod in the opposite direction, and this resistance which it affords to the motion is greater the longer the arm of the lever, A*o*, on which it acts. Hence the higher the weight, A, is raised, the slower are the oscillations. At the base of the instrument there is a clockwork motion, which works an escapement with such force that, at each oscillation of the pendulum, a tooth strikes strongly against a pallet fixed to the axis, *o*, thus producing a regular beat which gives the time. In front of the box which contains the mechanism is a scale with numbers, indicating the height at which the weight must be placed to obtain a given number of oscillations in a minute. In the figure this weight is at the number 92, which indicates that the pendulum makes 92 oscillations in a minute.

68. **Work.**—If we lift a weight from the ground a certain effort is required in opposition to the force of gravity, and we are said to

do work upon it. The work done will clearly depend on the weight to be lifted. To lift two pounds will require twice as much effort as to lift one pound.

It will also depend on the height through which it is lifted. The work of lifting a given weight vertically through two feet is twice as great as through one foot. Hence the measure of the work done on a body against gravity is the product of the weight into the vertical distance through which it is lifted.

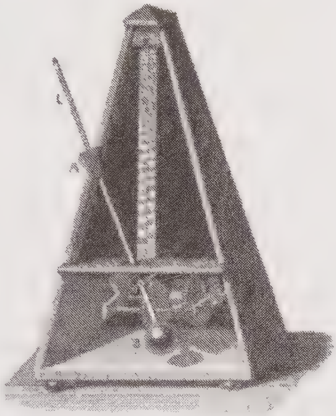


Fig. 64.

The unit of work in this country is the *foot-pound*: that is, the work done in raising one pound vertically through one foot. Twenty foot-pounds might thus be expressed either as twenty pounds raised through one foot or as one pound through twenty feet or four pounds through five feet, and so on.

On the metrical system the *kilogrammetre* is the unit; it is the work done when a weight of a kilogramme is raised through a height of a metre. This is equal to 7·23 foot-pounds, and one foot-pound = ·1383 of a kilogrammetre.

The idea of time does not enter into the idea of work done. Whether a labourer takes a day or a week to raise 500 bricks through a certain height, he only does a certain amount of work; but the idea of time does affect the rate at which he is paid for the work. Hence, in estimating the usefulness of any motor it becomes necessary to know the time required by it for doing a given amount of work. The amount of work per unit of time is the *power* of the motor. The unit of power is the power required to do a unit of work in a unit of time. For measuring the power of engines the unit used is the *horse-power*, which represents a rate of work of 33,000 foot-pounds per minute, or 550 foot-pounds per second.

69. **Energy.**—When we have raised a weight p through a height h from the ground, we have done ph units of work on it, and if the

body is allowed to fall it will do an amount of work depending on the velocity it acquires in falling. The fact that any agent is capable of doing work is expressed by saying that it possesses *energy*, and the quantity it possesses is measured by the work it can do.

We get a convenient expression for this in the following way. The velocity which a falling body acquires on striking the ground depends on the height from which it falls. From equation 3 (58) we have $v^2 = 2\,gh$. Multiplying both sides by m, we have $mv^2 = 2\,mgh$; substituting for m its value $\frac{p}{g}$, we get $\frac{1}{2}mv^2 = ph$.

This equation is one of fundamental importance, and is known as the equation of work. The energy possessed by a body in virtue of its position above the ground is called its *potential energy*. Thus ph represents the potential energy of a weight p which is h feet above the ground. The *energy of motion* of a body or its *kinetic energy* is measured by half its mass into the square of its velocity, and the above equation informs us that the potential energy of a body raised any distance above the ground is equal to its kinetic energy when it has fallen through that distance.

We may illustrate this by reference to the pendulum experiment in fig. 61. When the ball is in the position represented by the line cp it has potential energy; as it falls it acquires kinetic energy, and when it is in the position pm its energy is wholly kinetic, which enables it to rise to a height on the other side equal to that from which it fell. As it falls the bob loses in potential energy what it acquires of kinetic energy, and at any point of the path the sum of the two forms of energy is constant.

We must be careful to distinguish the kinetic energy of a body from what is called its *momentum*. The momentum of a body is defined as the product of its mass and its velocity, *i.e.* it is equal to mv, where m is the mass and v the velocity of the body. In the case of the pendulum (60) the momentum is zero at the beginning and end of a swing, and a maximum when the string is vertical.

70. **Varieties of energy.**—We have hitherto only considered the case of the work done by a body falling under the influence of gravity. There are, however, many other kinds of physical changes which can be produced under appropriate conditions, and the recent progress of investigation has shown that the conditions under which changes of all kinds occur are so far analogous to those required for the production of work by mechanical forces that the term *work*

has come to be used in a more extended sense than formerly, and is now often used to signify the production of any sort of physical change.

Thus work is said to be done when a body at a low temperature is raised to a higher temperature, just as much as when a weight is raised from a lower to a higher level; or, again, work is done when an electric, magnetic, or chemical change is produced. This extension of the meaning of the term work involves a similar extension of the meaning of *energy*, which in this wider sense may be defined as the *capacity for producing physical change*.

As examples of energy in this more general sense, the following may be mentioned :—(*a*) The energy possessed by gunpowder in virtue of the mutual chemical affinities of its constituents, whereby it is capable of doing work by generating heat or by acting on a cannon-ball so as to change its state of rest into one of rapid motion; (*b*) the energy of a charged Leyden jar, which, according to the way in which the jar is discharged, can give rise to changes of temperature, to changes of chemical composition, to mechanical changes, or to changes of magnetic or electric condition; (*c*) the energy of a red-hot ball, which, amongst other effects it is capable of producing, can raise the temperature and increase the volume of bodies colder than itself, or can change ice into water or water into steam; (*d*) the energy of the stretched string of a bow: here work has been consumed in stretching the string; when it is released the work reappears in the energy imparted to the arrow.

71. **Transformation of energy.**—It has been found by experiment that when one kind of energy disappears or is expended, energy of some other kind is produced, and that, under proper conditions, the disappearance of any one of the known kinds of energy can be made to give rise to a greater or less amount of any other kind.

It has also been found that the transformation of energy always takes place according to fixed proportions. For instance, when coal or any other combustible is burned, its chemical energy, or power of combining with oxygen, vanishes, and heat or thermal energy is produced, and the quantity of heat produced by the combustion of a given amount of coal is fixed and invariable. If the combustion takes place under the boiler of a steam-engine, mechanical work can be obtained by the expenditure of part of the heat produced, and here again the quantitative relation between the heat expended and the work gained in place of it is perfectly constant.

CHAPTER VI

MOLECULAR ATTRACTION

72. **Cohesion and chemical affinity.**—After having described, under the name of *universal gravitation*, the attraction which exists between the stars and planetary bodies ; and, under that of *gravity*, the attraction which the earth exerts upon all bodies in making them fall towards it, we have to investigate the attractions which hold together the ultimate particles or molecules of a body. These are—chemical affinity and cohesion.

Cohesion is the force which unites two molecules of the same nature ; for example, two molecules of water or two molecules of iron. Cohesion is strongly exerted in solids, less strongly in liquids, and scarcely at all in gases. It decreases as the temperature rises. Hence it is that when solid bodies are heated, they first expand, then liquefy, and are ultimately converted into the gaseous state, provided that heat produces in them no chemical change.

Cohesion varies not only with the nature of bodies, but also with the arrangement of their molecules : for example, the difference between tempered and untempered steel is due to a difference in the molecular arrangement produced by tempering. Many of the properties of bodies, such as tenacity, hardness, and ductility, are due to the modifications which this force undergoes.

In large masses of liquids, the force of gravity preponderates over that of cohesion. Hence liquids acted upon by the former force have no special shape ; they take that of the vessel in which they are contained. But in smaller masses cohesion gets the upper hand, and liquids present then the spheroidal form. This is seen in raindrops and in the drops of dew on the leaves of plants ; it is also seen when a liquid is placed on a solid which it does not

moisten ; as, for example, mercury upon wood. The same result may also be obtained with water, by sprinkling upon the surface of the wood some light powder such as lycopodium or lampblack, and then dropping some water on it. Molten lead, falling from a sieve at the top of a shot-tower, acquires the form of perfect spherical drops, which it retains on cooling.

A very interesting experiment illustrating cohesion consists in introducing some coloured olive oil, by means of a pipette, into a mixture of alcohol and water, these liquids being mixed in such proportions as to have exactly the same specific gravity (110) as the oil (fig. 65) ; the latter does not mix with the surrounding liquid, but remains suspended in it as a sphere, which, if the experiment is carefully performed, has a larger diameter than that of the neck of the vessel.

In dropping various liquids from bottles it is seen that the size of the drops is not the same—that of water is greater than that of alcohol, and it is greatest in those in which cohesion is greatest ; and on this fact is based a method of measuring the force of cohesion in different liquids.

Fig. 65

Chemical affinity or *chemical attraction* is the force which is exerted between molecules not of the same kind. Thus, in water, which is composed of oxygen and hydrogen, it is affinity or attraction which unites these elements, but it is cohesion which binds together two molecules of water. In compound bodies cohesion and affinity operate simultaneously, while in elementary bodies cohesion has alone to be considered.

To chemical affinity are due all the phenomena of combustion ; when carbon burns, it is affinity which causes it to combine with the oxygen of the air to form the gas known as carbonic acid Affinity determines the combination of the elements, so that with a small number of them are formed the immense number of organic and mineral substances which serve for our daily uses.

The causes which tend to weaken cohesion are most favourable to affinity ; for instance, the action of affinity between substances is facilitated by their division, and still more by converting them to a liquid or gaseous state. It is most powerfully exerted by a body in its *nascent* state—that is, the state in which the body exists at the moment it is disengaged from a compound ; the body is then free

and ready to obey the feeblest affinity. An increase of temperature modifies affinity differently under different circumstances. In some cases, by diminishing cohesion and increasing the distance between the molecules, heat promotes combination. Sulphur and oxygen, which at the ordinary temperature are without action on each other, combine to form sulphurous acid when the temperature is raised. In other cases heat tends to decompose compounds; thus many metallic oxides—as, for example, those of silver and mercury—are decomposed by the action of heat into gas and metal.

73. **Adhesion.**—*Adhesion* is the term applied to the attraction between two bodies when their *surfaces* are placed in contact.

If two leaden bullets are cut with a penknife so as to form two equal and brightly polished surfaces, and the two faces are turned against each other until they are in the closest contact, they adhere so strongly as to require a force of more than 3 or 4 ounces to separate them. The same experiment may be made with two pieces of perfectly plane brightly polished plate glass, *g*, fixed in wooden frames, *ab*, *cd*, fig. 66; they are slid over each other with a certain pressure, and then adhere so firmly as not only to hold up the lower glass, but a considerable weight in addition. In some cases the adhesion is so powerful that they cannot be separated without breaking. As the experiment succeeds in a vacuum, the effect cannot be due to atmospheric pressure, but must be attributed to a reciprocal action between the two surfaces. Adhesion between two surfaces is the more complete the longer they have been in contact, and the greater the pressure between them, and the greater the extent of surface; it is also better the more polished the surfaces, and the freer they are from a layer of air or of metallic oxide.

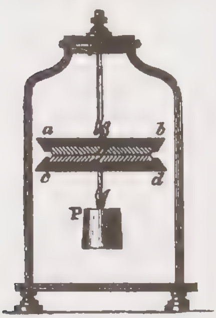


Fig. 66.

There is no real difference between adhesion and cohesion; thus, when two freshly cut surfaces of india rubber are pressed together, they adhere with considerable force, and ultimately form one compact solid mass. The term *adhesion* is generally restricted to the case in which the bodies in contact are of different nature.

Adhesion also takes place between solids and liquids. If we dip a glass rod into water, and then withdraw it, a drop will be found to collect at its lower extremity, and remain suspended there. As the weight of the drop tends to detach it, there must necessarily be some force superior to this weight which maintains it there; this force is the force of adhesion. It is more powerful than that between solids; thus, in the experiment represented in fig. 66, if a layer of oil is interposed between the plates, when pulled asunder each plate is moistened by the oil, showing therefore that in separating the plates their cohesion is overcome, but not the adhesion of the oil to the metal. But liquids adhere to solids even when they are not wetted. Thus, if a smooth glass plate be suspended horizontally from one arm of a balance, and be counterpoised, as in fig. 67, and a mercury surface brought under the plate, so that they touch, a considerable weight must be placed in the other pan in order to detach the plate from the mercury. Small drops of mercury, too, adhere to the under side of a glass or porcelain plate.

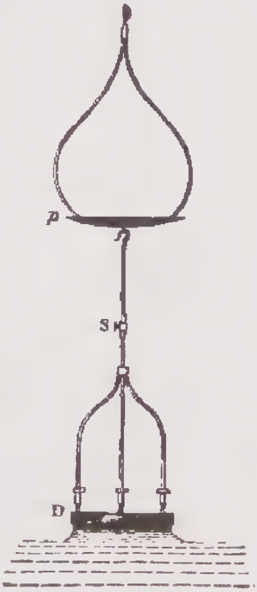


Fig. 67.

To adhesion is due the resistance experienced in lifting vertically a flat board placed on water; and to the same force is ascribed the difficulty met with in walking through thick mud. Adhesion is particularly strong when a liquid is brought in contact with a solid, and then solidifies by cooling or evaporation. On this depend the operations of glueing, cementing, and soldering. When two pieces of glass are joined by cement, and the operation has been carefully performed, it often happens that the pieces of glass are torn asunder more easily than the cement. The collection of dust on the ceiling and walls of a room, writing with chalk or with a lead pencil, are also due to adhesion. The particles in these cases, however, are easily removed, as they only adhere to the surface

layer. In writing with ink or painting with water colours the liquid, carrying with it the suspended solids, penetrates the pores, where they are left on the evaporation of the liquid.

To adhesion it is due that liquids in being poured out of a vessel are apt to run down the sides. To prevent this, the outer edge is greased, or the liquid is allowed to flow along a moistened glass rod.

The force of adhesion operates also between solids and gases. If a metal plate be immersed in water, bubbles will be found to appear on the surface. As air cannot penetrate into the pores of the plate, the bubbles could not rise from air which had been expelled, but must be due to a layer of air which covered the plate and *moistened* it like a liquid.

In many cases when gases are separated in the *nascent state* on the surface of metals—as in electrolysis—the layer of gas which covers the plate has such a density that it can produce chemical actions more powerful than those which it can bring about in the free state.

Many illustrations may be given of the existence of this layer of condensed gas. If we trace a figure with the finger on an ordinary glass plate, and then breathe on the glass, the figure becomes visible. Here the original surface layer had been removed, and then the greater condensation of aqueous vapour on the parts from which it was removed brings out the figure.

If the plate be polished, so as to remove this layer, and an ordinary coin be placed on it, on afterwards removing the coin and breathing on the glass an impression of the coin is seen. Here the layer of gas originally on the surface of the coin diffuses on to the glass plate, which thereby becomes altered. Conversely, if a coin be polished, and laid on an ordinary glass plate, it will partially remove the layer of gas from the parts in contact, so that on breathing on the plate the image is visible.

CAPILLARITY. ABSORPTION

74. **Capillary phenomena.**—When solid bodies are placed in contact with liquids, molecular attraction gives rise to a class of phenomena called *capillary phenomena*, because they are best seen in tubes so narrow that their diameters are comparable with that of a hair. These phenomena are treated of in physics under the head of *capillarity* or *capillary attraction*; the latter expression is also applied to the force which produces the phenomena.

The phenomena of capillarity are very various, but may all be referred to the reciprocal attraction of the liquid molecules for each other, and to the attraction between these molecules and solid bodies. The following are some of these phenomena :—

i. When a glass rod is placed in a liquid which wets it—water, for instance—the liquid, as if not subject to the laws of gravity, is raised upwards against the sides of the solid, and its surface, instead of being horizontal, becomes slightly concave (fig. 68).

ii. If, instead of a solid rod, a hollow tube be immersed in water (fig. 69), not merely is the liquid raised around the tube, but it rises in the inside to a height which is greater the narrower the tube; and, at the same time, the surface of the liquid inside the tube assumes a concave form.

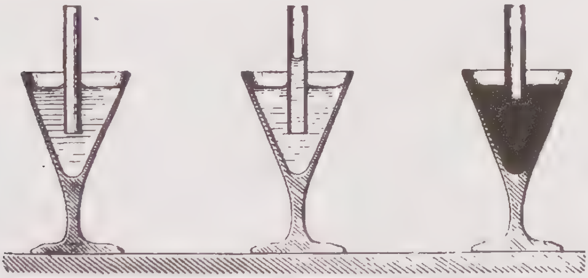


Fig. 68. Fig. 69. Fig. 70.

iii. If the tube is not moistened by the liquid, as is the case with mercury and glass, the liquid is depressed instead of being raised (fig. 70), and the more so the narrower the tube; and the surface which was previously concave now becomes convex. The surface of a liquid exhibits the same concavity or convexity against the sides of a vessel in which it is contained, according as the sides are or are not moistened by the liquid.

75. **Laws of capillarity.**—The elevation and depression of liquids in capillary tubes, the internal diameter of which does not exceed two millimetres, are governed by the following laws :—

1. *When a capillary tube is placed in a liquid, the liquid is raised or depressed according as it does or does not moisten the tube, and the action is the greater the smaller the diameter of the tube*—that is, that if we have two glass tubes, one with a diameter of 1 mm. and the other with a diameter of 2 mm., if the ends are

placed in water, it would rise in the former tube to a height of 15 mm., and in the latter to a height of 30 mm. In a tube $\frac{1}{10}$ mm. in diameter it would rise to a height of 300 mm. The cells in plants have a diameter of $\frac{1}{100}$ mm., so that sap rises in them with great force.

II. *The height varies with the nature of the liquid, and decreases as the temperature rises.* Thus, in tubes of the same diameter, 1 mm., the heights to which water, turpentine, and alcohol would rise would be 30, 13, and 12 mm. respectively. Provided the liquid moistens the tube, the material of the tube has no influence.

76. **Effects due to capillarity.**—It is owing to capillarity that sap rises in plants, that water is retained in a sponge, that oil rises in the wicks of lamps, ink in the narrow slit of a pen, and melted tallow in the wicks of candles. The interstices which exist between the fibres of the cotton, of which the wicks are formed, act as capillary tubes in which the ascent takes place. In very porous bodies, the pores, being in communication with each other, form a series of capillary tubes, which produce the same effect. If a lump of sugar be placed in a cup in which a little coffee is left, the liquid is seen to rise rapidly and fill the entire piece ; and it is even to be remarked that the sugar then dissolves more quickly than if it had been directly immersed in the coffee. This is due to the fact that in the latter case the air which fills the pores, not being able to escape so rapidly as if the piece of sugar is only partially immersed, prevents the liquid from penetrating into the mass of the sugar, and thus retards the solution. If oil or ink be dropped on the edge of a book, it penetrates to some distance in the leaves.

Fig. 71.

In petroleum lamps the liquid rises by capillary action in the wick to a considerable height above the level in the reservoir ; olive oil, for instance, could not be continuously burnt in such a lamp, for, being more viscous (84), it does not rise in the capillary channels rapidly enough to feed the flame. In oil lamps as well as

in candles, the flame is just above the reservoir of the liquid which feeds them. Petroleum is better suited than olive oil for loosening a screw rusted in a nut, since its capillary constant is greater.

Spiders can often move on the surface of water without sinking (fig. 71). Similarly a fine sewing-needle gently placed on water does not sink. This is a capillary phenomenon caused by the fact that the cohesion of a free surface of a liquid is greater than in the interior: the surface is, as it were, covered by a stretched liquid membrane like that of an elastic skin, and this *surface layer* can thus support a slight weight. If the needle be washed in alcohol or potash so as to remove the slight layer of grease, it is wetted by the water and at once sinks. It is as if the surface layer were broken.

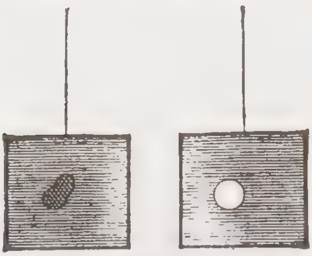
Fig. 72.

The existence of this *surface tension* may be illustrated by many experiments, such as that shown in fig. 72. Two light glass rods are connected by threads, which again are joined by a cross thread. When this arrangement is immersed in a properly prepared solution of soap, and is then withdrawn, a thin film is formed, which, acting by its tension on the flexible sides, gives them a circular form. The cross thread has no particular shape, but if the part of the film below it be broken by means of blotting-paper, this, too, assumes the curved shape as shown in the figure; and if it be pulled by another thread attached to it, the film stretches, but reverts to its original shape after the pull ceases.

On this experiment is based a method of determining the surface tension of liquids.

Another experiment by Van der Mensbrugghe is made by means of a wire frame (fig. 73), which is immersed in solution of soap, such as is used for blowing soap bubbles. On removing the frame from the solution a thin film is formed across it. A loop of fine silk thread moistened with the liquid in question is carefully placed on the film, and assumes any shape (fig. 73, *a*). By means of a hot wire the film is broken inside the loop, and the silk thread is then seen to stretch and assume a circular form (fig. 73, *b*). Before the

film inside the loop was broken, the surface tension acted equally on both sides of the thread, but after its rupture the tension on the outer side of the thread was unbalanced, and, being equal in all directions, drew the thread into the circular form, rendering the remaining liquid surface as small as possible.



a Fig. 73. *b*

A curious illustration of this phenomenon is that pointed out by Professor Boys. When a camel's-hair pencil is immersed in water (fig. 74, *a*) it presents the ordinary brush-like appearance, the hairs being separately visible, as when it is dry ; but when taken out they cling together, forming, as it were, a solid mass (fig. 74, *b*), in consequence of the surface tension of the liquid. A similar effect is observed on taking aquatic plants out of water.

Among the phenomena due to surface tension may be mentioned the well-known one of the 'tears of wine.' The surface tension of

a *b*

Fig. 74.

Fig. 75.

water in contact with air is greater than that of any other liquid except mercury. It is more than three times as great as that of alcohol. When a wine-glass contains a little strong wine, the wine rises up against the sides like any other liquid ; but the alcohol evaporates rapidly from the surface, the consequence of which is

that the liquid layer becomes more watery. Near the surface of the liquid the strength of the liquid layer is kept up by diffusion ; but higher up, owing to the increased surface tension of the more aqueous wine, it creeps up the sides and draws with it some of the stronger alcoholic liquid below, the increasing weight of which ultimately causes it to break and run down in drops (fig. 75).

77. **Absorption and imbibition.**—These terms indicate the penetration of a liquid or a gas into a porous body. Absorption is used both for liquids and gases, while imbibition is restricted to liquids.

Charcoal has a great power of absorbing gases. If a piece of recently heated charcoal be passed into a bell jar full of carbonic acid placed over a mercury trough (fig. 76), the volume of gas is seen to diminish rapidly, and it is found that the gas which has disappeared in penetrating the charcoal represents a volume thirty-five times that of the solid. There are even gases, such as ammonia, of which charcoal can absorb ninety times its own volume.

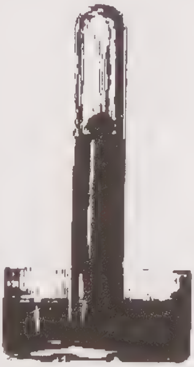


Fig. 76.

In general those gases which are most easily condensed to the liquid state are just those which are absorbed to the greatest extent by charcoal ; and it is highly probable that the gases thus absorbed are present in the liquid state. To this powerful absorption of gases, displayed by charcoal and other porous substances, such as dry earth, the purifying action of these substances is due.

The absorption of gases by solids is attended by a considerable rise of temperature, as may be shown by the experiment represented in fig. 77, in which a glass tube, *a*, is fitted by means of a cork into a wider one ; *b* is a plug of cotton-wool on the cork, and on this a layer of charcoal, *k*, is placed, which has been freed from air by means of an air-pump. In this is the bulb of a thermometer When a current of ammonia or of carbonic acid gas is admitted by the tube *a*, the thermometer at once rises. Absorption takes place in all parts of plants, but more especially in the rootlets and by the leaves. These organs absorb carbonic acid associated with water, for the growth of the plants. Animal tissues can even absorb solid substances. For instance, in those processes of the arts

where the workmen have to handle salts of mercury or of lead, these metals are gradually absorbed into the system, and often produce serious and even fatal diseases.

Fig. 77.

Owing to absorption, tobacco soon dries if kept in a wooden box; while it remains fresh if kept in a metal one, for then its moisture is not absorbed by the metal as it is by the wood.

When animal or vegetable matters absorb water, their volume increases. Thus if a tolerably large sheet of dry paper be measured, and be then moistened, it will be found to have appreciably expanded by this process. This property is made use of in stretching paper on drawing-boards; the paper is moistened, and is then glued or fastened with pins round the edge of the board. In drying, the paper contracts, and is tightly stretched. For the same reason, too, wall-papers which have been fastened on cloth along the walls are sometimes liable to be torn.

In bending wood, the side to be bent is heated, and the other side moistened. This latter being lengthened owing to the water it absorbs, while the former is contracted in consequence of the dryness, a curvature ensues which is concave on the heated side.

It is frequently observed that, owing to the changes of volume which they undergo under the influence of moisture and dryness, the pieces of furniture of our rooms are heard to crack when the weather changes.

By the absorption of moisture ropes become shorter, and lengthen when they dry. This may seem opposed to what has been stated about moist paper, but the explanation is not difficult. Ropes are formed of fibres twisted together, and as these fibres swell owing to the water they absorb, the rope becomes larger, and hence each fibre should make in coiling a longer circuit, and the rope will become shortened as it is moistened. For this reason, too, new cloths shrink considerably when they are moistened for the first time.

78. **Diffusion of liquids. Diosmose.**—When oil and water are shaken violently together, they form a turbid liquid; but when this is allowed to rest, they settle in the order of their specific gravities, the oil uppermost—they do not mix. If a solution of copper sulphate be placed in a vessel, and then a lighter liquid

such as water, with which it is miscible in all proportions, is carefully poured upon it, the two liquids will form two separate layers. After some time, however, even when the liquids are quite at rest it will be found that the lower and heavier liquid diffuses into the upper and lighter one, until after some time the whole forms a uniform mixture. This phenomenon is called *diffusion*, and the rate at which it takes place differs with the nature of the substances concerned.

If the liquids are separated by a porous diaphragm or partition, other phenomena are observed, as may be shown by the experiment represented in fig. 78, where *b* is a vessel the bottom of which is closed by a piece of bladder, while in the neck is fitted a tube, *r*, resting in the lid by the cork, *a*. The vessel *b* contains saturated solution of copper sulphate, the outer vessel containing water, both liquids being originally at the same level, *n n*. After some time it will be seen that the liquid in *b* becomes lighter in colour and at the same time rises to a considerable height in the tube *r*; the liquid in the outer vessel sinks below the level *n n*, and a bluish tinge shows the presence of some of the copper solution. It thus appears that both the liquids pass through the fine pores of the diaphragm in opposite directions, but with unequal velocities; the lighter liquid, the water, passes through the diaphragm more rapidly than the copper sulphate passes out, and accordingly there is an accumulation on the side of the salt. Ultimately, however, the liquid on each side is of the same concentration and at the same level.

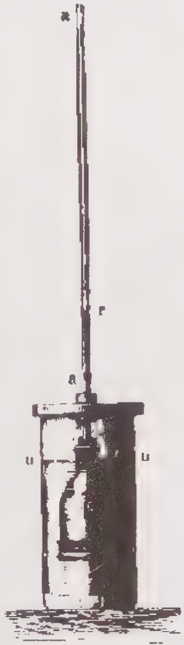


Fig. 78.

If a sheep's bladder partially filled with strong brine, and tightly tied, be left in pure water, it will be found, after some time, to have become tightly distended.

If a carrot or beetroot is cut and hollowed out, as shown in fig. 79, and powdered sugar is placed in the cavity, after a while this is converted into a concentrated solution, while the walls of the carrot shrink considerably, obviously owing to the fact that the water has diffused out of the cells.

This simultaneous passage of liquids in opposite directions through a porous diaphragm was first observed by Dutrochet, and

Fig. 79.

is known as *diosmose.* It is of great importance for animal and vegetable life. The cell-walls of plants, and the sides of animal cells and blood-vessels, show no pores even under a magnifying-glass ; yet the interchange of animal and vegetable juices takes place through them by means of diosmose, and it is by this process that the assimilation of nutritive substances and other physiological processes are carried on.

CHAPTER VII

PROPERTIES SPECIAL TO SOLIDS

79. **Tenacity.**—Besides the general properties which we have hitherto been considering, and which are met with in solids, liquids, and gases, there are some which are special to solids. They are—tenacity, hardness, ductility, and malleability.

Tenacity is the resistance which bodies oppose to being broken when exposed to traction or stretching. To investigate this property a wire or thin rod of any material, *c c′* (fig. 80), is fixed at one end, while at the other is a vessel, *p*, to which weights can be gradually added; for this purpose shot or sand, or even water, are most convenient. If the distance between two fixed points, *a* and *a′*, be noted, it will be found to increase with the weight added, and represents a lengthening of the wire. Accurate measurements show that if the weights are not too great, *the elongation is proportional to the stretching weight.* What is called the *coefficient of elasticity* is defined as the force required to stretch a wire of unit cross-section to double its length, if this were possible. For steel wire this number is about 2·5 million kilogrammes per sq. cm., or 25,000 kilogrammes per sq. mm.; so that if a weight of 25 kilogrammes were applied to a wire one metre long and one sq. mm. in section, the increase in length would be 1 mm.

Fig. 80.

If wires of the same material but different diameters are used it will be found that when stretched by the same weight the

increase of length is inversely as the cross-section. Thus, the elongation of a wire of 1 sq. mm. would for the same weight be twice as great as with one of 2 sq. mm., so that to produce with this the same elongation, double the weight would be needed.

When the weights are removed the wire reverts to its original length; this, however, is only the case if the weight is under a certain limit: beyond this the wire is permanently elongated; the weight required to effect this is a measure of this *limit of elasticity.*

On continuing the addition of weights, a point is reached at which the wire breaks. The weight required for this is called the *breaking weight*, and is the measure of the *tenacity* of the material. Thus, to break a wire 1 sq. mm. in cross-section the following weights in kilogrammes are needed: lead, 2·2; tin, 2·6; silver, 39; copper, 40; brass, 50; iron, 63; steel, 83. For other materials we have: leather band, 2·9; hemp rope, 5·0; wood in the direction of the fibres, 5·5.

The proportionality between weight and elongation is also found in wires wound in spiral form, and on this depends their use for weighing (25).

Tenacity is directly proportional to the breaking weight and to the cross-section of the wire.

Not only does tenacity vary with different substances, but it also varies with the form of the body. Thus, for the same sectional area, a cylinder has greater tenacity than a prism. The quantity of matter being the same, a hollow cylinder has greater tenacity than a solid one.

The shape has also the same influence on the resistance to crushing as it has on the resistance to traction. A hollow cylinder with the same mass, and the same weight, offers a greater resistance than a solid cylinder. For this reason the bones of animals, the feathers of birds, the stems of corn, and other plants, offer greater resistance than if they were solid, the mass remaining the same.

80. **Hardness.**—*Hardness* is the resistance which bodies offer to being scratched by others. It is only a relative property, for a body which is hard in reference to one body may be soft in reference to others. The relative hardness of two bodies is ascertained by trying which of them will scratch the other. Diamond is the hardest of all substances, for it scratches all, and is not scratched by any. The hardness of a body is expressed by referring it to a *scale of hardness*; that usually adopted is—

1. Talc	5. Apatite	8. Topaz
2. Rock Salt	6. Felspar	9. Corundum
3. Calcspar	7. Quartz	10. Diamond
4. Fluorspar		

Thus the hardness of a body which would scratch felspar, but would be scratched by quartz, would be expressed by the number 6·5.

The pure metals are softer than their alloys. Hence for jewellery and coinage, gold and silver, which are soft metals, are alloyed with copper to increase their hardness.

The hardness of a body has no relation to its resistance to impulsive force. Glass and diamond are much harder than wood, but the latter offers far greater resistance to the blow of a hammer. Hard bodies are often used for polishing-powders ; for example, emery, pumice, and tripoli. Diamond, being the hardest of all bodies, can only be ground by means of its own powder.

81. **Ductility.**—*Ductility* is the property owing to which a great number of bodies change their forms by the action of stretching or pressure.

Certain bodies, such as clay, wax, etc., are so ductile at ordinary temperatures that they can be drawn out, flattened, modelled between the fingers ; others, such as resins and glass, require the aid of heat. Glass is then so ductile that it can be drawn out into fine threads, which are flexible enough to be woven into cloth.

By melting in a blowpipe-flame a piece of quartz attached to one end of a small arrow, which is then shot from a crossbow, Boys has produced uniform quartz threads of almost any degree of fineness, and, relatively speaking, of enormous strength. Threads have been made whose diameter is estimated at a millionth of an inch, and threads of $\frac{1}{10000}$ inch have been used in physical experiments ; they are relatively stronger than bar steel, having a tenacity of 80 tons to the square inch.

Platinum is the most ductile of all metals. Wollaston obtained a wire of this material 0·00003 of an inch in diameter, by coating a very thin platinum wire with a layer of silver so as to form a cylinder, which was then drawn out as finely as possible, so that both metals were equally extended. This was then placed in dilute nitric acid, which dissolved the silver, but left the platinum untouched. A mile of this wire would not weigh more than a grain and a quarter.

Several metals, such as gold, silver, copper, are ductile even at

ordinary temperatures, but require the use of powerful machines, such as the draw-plate or the rolling-mill.

Many bodies, more especially steel, when suddenly cooled after having been raised to a high temperature, become hard and *brittle* —that is to say, break on the application of a slight blow. The most brittle metals are bismuth, antimony, and zinc; they can be easily powdered.

By reheating and cooling slowly, which is called *annealing*, hard and brittle steel may be converted into a soft, flexible material, and in general, by varying the limits of temperature within which the change takes place, almost any degree of elasticity, hardness, and flexibility may be given to it. This operation is called *tempering*. All cutting instruments are made of tempered steel.

Fig. 81.

What are known as *Rupert's drops* are an excellent illustration of brittleness; they are formed by dropping melted glass into cold water (fig. 81); when the point of one of them is broken off, the whole mass at once falls into fine powder.

82. **Malleability.**—*Malleability* is that modification of ductility which is exhibited when metals are hammered. This property increases greatly with the temperature; everyone knows, for instance, that iron is easily forged when hot, and not when cold.

Gold is very malleable, even at the ordinary temperature. To make the extremely thin plates of gold known as *gold leaf*, the gold is first pressed, by means of the rolling-mill, into long plates about an inch in breadth and $\frac{1}{25}$ inch in thickness. These plates are cut into small squares and beaten out by means of a hammer; these are cut and beaten again, and so on. By beating them directly, the operation could not long be continued, for the metal would be torn; hence the plates to be beaten must be placed between plates of a substance which, while thin, affords great resistance. Sheets of vellum and parchment are first used for this purpose, and afterwards *gold-beater's skin*.

Leaves of gold are thus obtained, which are so thin that 300,000 superposed are only an inch thick. Silver and copper may also be worked in the same manner. These leaves are used in the arts for gilding on wood, paper, and other materials.

The following is the usual order of the metals under the draw-plate, the rolling-mill, and the hammer, arranged in reference to their increased ductility :—

Draw-plate	Rolling-mill	Hammer
Platinum	Gold	Lead
Silver	Silver	Tin
Iron	Copper	Gold
Copper	Tin	Zinc
Gold	Lead	Silver
Zinc	Zinc	Copper
Tin	Platinum	Platinum
Lead	Iron	Iron

The metals must be pure ; if they are alloyed with other metals they are fragile, and have but little ductility.

BOOK II

ON LIQUIDS

CHAPTER I

PRESSURES TRANSMITTED AND EXERTED BY LIQUIDS

83. **Hydrostatics.**—The science of *hydrostatics*, from two Greek words signifying *equilibrium of water*, treats of the conditions of the equilibrium of liquids, and of the pressures they exert, whether within their own mass or on the sides of the vessels in which they are contained.

84. **Special characteristics of liquids.**—One essential character of a liquid is the extreme mobility of its molecules, which are displaced by the slightest force. The fluidity of liquids is due to this property ; it, however, is not perfect—there is always a sufficient adherence between the molecules to produce a greater or less *viscosity*.

In respect to this property liquids differ greatly ; thus ether is extremely mobile, while glycerine and treacle have great viscosity.

Another essential property of liquids, and one by which they are distinguished from gases, is their very small compressibility. We have already seen (13) that their compressibility is so small that for a long time they were regarded as being quite incompressible. It was not before 1823 that Oersted, a Swedish physicist, first proved in an exact manner that liquids are compressible. The apparatus he used for this purpose is called the *piezometer* (πιέζω, I compress, μέτρον, measure). By its means it has been found that a pressure of one atmosphere compresses distilled water by about $\frac{1}{20000}$th part of its volume ; mercury by the same pressure only undergoes about one-thirteenth as great diminution ; while the compressibility

of ether is more than twice as great as that of water. When the pressure is removed the liquid returns to its original volume.

Liquids are also porous, elastic, and impenetrable, like all other bodies. The proofs of their porosity have been already given (9). Their impenetrability is manifested whenever a solid is immersed in water. For if a vessel be quite filled with water, and any solid body be placed in it which does not absorb the liquid, and in which the solid is insoluble, it will be observed that a volume of water flows over which is exactly equal to that of the solid immersed.

On this property is based a method of determining with accuracy the volume of bodies of irregular shape.

85. **Equality of pressures. Pascal's law.**—Liquids have the following remarkable property, which is expressed by what is often called 'Pascal's law,' for it was first enunciated by that distinguished philosopher.

Pressure exerted anywhere upon a mass of liquid is transmitted undiminished in all directions, and acts at right angles to surfaces exposed to the liquid.

To get a clearer idea of the truth of this principle, let us conceive a cylindrical vessel, in the sides of which are placed various cylindrical tubulures, all of the same size, and closed by movable pistons (fig. 82). The vessel being filled with water, or any other liquid, the moment any pressure is applied to the piston A, all the other pistons are pressed outwards, showing that the pressure is not merely transmitted downwards upon the piston D, but laterally upon the pistons E and F, and upwards upon the pistons B and C. If, instead of pressing on the piston A, the pressure be exerted upon B, the same effects are produced ; the piston A is then forced upwards.

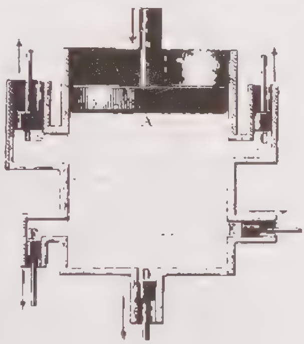


Fig. 82.

In these different cases the pressure is transmitted in all directions with undiminished intensity, it being remembered that pressure means force per unit area. For instance, if the force on the piston A is 20 lb., and its surface is equal to that of the piston B, the upward force on the latter is also 20 lb. ; but if the surface of the piston B is only a twentieth that of A, the force

upon B is only 1 lb. The force acting on each piston is equal to the pressure multiplied by the area of the piston.

86. **Consequence and verification of Pascal's principle.**—For the purpose of verifying Pascal's principle, two cylinders are taken of unequal dimensions, joined by a tube (fig. 83). These cylinders contain water, and are provided with pistons which move in them with gentle friction. Now, if the surface of the larger one, P, for instance, is twenty times that of the smaller one, *p*, it will be found that a weight of 1 lb. placed upon *p* will balance a weight of 20 lb. placed upon P ; if these weights are in any other ratio, equilibrium is destroyed.

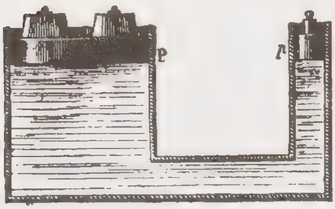


Fig. 83.

The principle of the equality of pressures forms the basis of the whole science of hydrostatics, and we shall presently find a very important application of it in the *hydraulic press* (92).

87. **Pressures resulting from the weight of liquids.**—In what has been said we have considered the pressure transmitted towards the sides of the vessel when some external force is applied. It is not, however, necessary to exert an external pressure on the surface of a liquid in order to produce internal pressure in its mass and on the sides of the vessel. The mere weight of the liquid itself is sufficient to produce pressures which vary with the depth and with the density of the liquid.

For suppose any vessel filled with liquid : if we conceive the liquid divided into horizontal layers of equal thickness, it is clear that the second layer supports the weight of the first; that the third supports the weight of the first and second, and so on ; so that the pressure increases with the number of layers, which is expressed by saying that *gravity produces in liquids pressures proportional to the depths.*

It is obvious, moreover, that *these pressures are proportional to the density of the liquids*—that is, that, for the same depth, a liquid which has two or three times the density of another will exert twice or thrice as much pressure.

It follows, from the principle of the equality of pressure in all directions, that the pressure produced by gravity in liquids is exerted

not merely in the direction of this force, but *laterally*, and also *upwards*, as will now be demonstrated.

88. **Lateral pressure. Hydraulic tourniquet.**—The existence of pressures which liquids exert upon the sides of the vessel in which they are contained, or lateral pressures, may be demonstrated by means of the *hydraulic tourniquet* or *Barker's mill* (fig. 84). This consists essentially of a long glass tube, C, with a funnel, D, at the top. The bottom of the tube fits into a hollow brass box, which rests on a pivot: in the sides of the box are fitted four brass tubes, arranged crosswise, and all bent in the same direction at the ends.

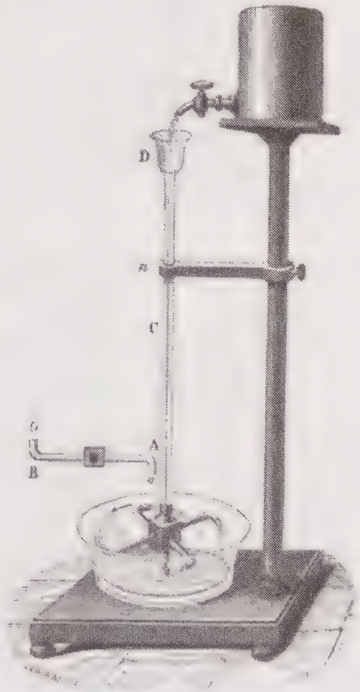


Fig. 84.

Water descending the long tube emerges by the apertures of the bent tubes, which are soon seen to rotate rapidly in the direction indicated by the arrow. This rotation is due to the lateral pressure exerted by the column of water in the long tube. For let us consider one of the bent tubes *a*A, B*b*, represented in section on the left (fig. 84), and suppose, first, that the orifices *a* and *b* are closed by caps. The column of water which then fills the tube C exerts upon the portions of the opposite sides, A and *a*, equal and contrary pressures, which hold each other in equilibrium; this is also the case at B and *b*, and thus no rotation can be produced in either direction. But if the caps at *a* and *b* are removed, as the water issues by these orifices, the pressures on the vessel at *a* and *b* no longer exist, while those at A and B, continuing to act, produce the rotation.

The action of this lateral pressure may also be illustrated by placing a cylinder (fig. 85), filled with water, on a piece of cork, or on a board which is floated on water. In one side of the vessel is a stopcock, and on removing this the water jets out; the pressure on this side is less than on the opposite one, and accordingly the vessel floats on the water in the direction opposed to that in which the jet is issuing.

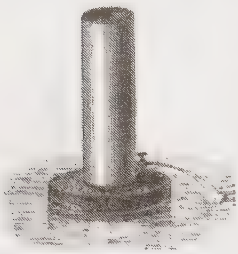


Fig. 85.

Rotating fireworks also act on the same principle as Barker's mill: that is, an unbalanced reaction from the heated gases which issue from openings in them gives them motion in the opposite directions.

The principle of Barker's mill is of extended use in the construction of those hydraulic and steam motors which are known as *turbines*.

It is owing to the lateral pressure of water that dykes and banks, which retain rivers or reservoirs or canals, sometimes give way by becoming too weak for the pressure they have to support.

89. **Vertical upward pressure.**—The pressure which the upper layers of a liquid exert on the lower layers causes them to exert an equal reaction in an upward direction, a necessary consequence of the principle of transmission of pressure in all directions.

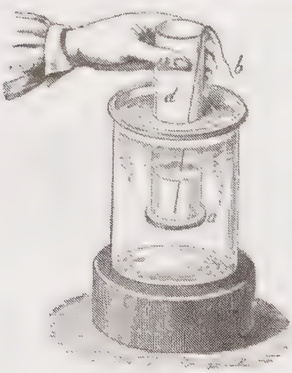


Fig. 86.

The following experiment (fig. 86) serves to exhibit the upward pressure of liquids. A large, open, glass tube, one end of which is ground, is fitted with a ground-glass disc, *a*, or, still better, with a thin card or piece of mica, the weight of which may be neglected. To the disc is fitted a string, *b*, by which it can be held against the bottom of the tube. The whole is then immersed in water, and the disc does not fall, although no longer held by the string; it is consequently kept in its position by the upward pressure of the water.

If water be now slowly poured into the tube the disc will only sink when the height of the water inside the tube is equal to the height outside. It follows thence that the upward pressure of the disc is equal to the pressure of a column of water, the height of which is the distance from the disc to the outer surface of the liquid. Hence *the upward pressure of liquids at any point is governed by the same laws as the downward pressure.*

This upward pressure is termed the *buoyancy* of liquids; it is perceived when the hand is plunged into water, and still more distinctly if it is immersed in mercury, which, being of greater density, produces greater pressure. Thus it is that, if a leak be produced in the bottom of a ship, water rushes in with great force.

90. **Pressure is independent of the shape of the vessel.**—The pressure exerted by a liquid, in virtue of its weight, on any

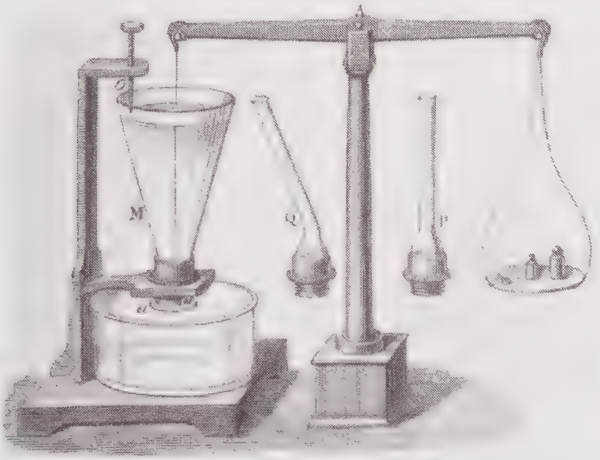


Fig. 87.

portion of the liquid, or on the sides of the vessel in which it is contained, depends on the depth of the liquid and on its density, but *is independent of the shape of the vessel and of the quantity of the liquid.*

This principle, which follows from the law of the equality of pressure, may be experimentally demonstrated by many forms of apparatus. The following is one frequently used, and is due to

Masson. It consists of a large, conical vessel, M, screwed to a brass tubulure, *c*, fixed to a wooden support (fig. 87). This tubulure is closed by a disc, *a*, which does not adhere to it, but is simply applied against the edge, and is kept there by a string attached to one end of the beam of an ordinary balance, at the other end of which is a scale-pan. Weights are placed in the latter, so as just to counterbalance the pressure of the water on the disc, when the vessel M is almost full ; water is then gradually added until the disc just begins to give way and allows some to escape. A screw, O, is then lowered until its point just grazes the surface of the liquid. If the vessel M be unscrewed, and replaced by the cylindrical tube, P, the capacity of which is far less, on gradually pouring water in, the moment the level of the liquid just touches the point of the rod, O, the disc, *a*, begins to allow some water to escape. The same result ensues if, for the straight tube, P, the inclined one, Q, be substituted. In these three cases, therefore, provided the height of the liquid is constant, the pressure on the disc, *a*, is the same, whatever be the shape and capacity of the vessels.

Fig. 88.

Moreover, the weight which has to be put on the scale-pan to establish equilibrium shows that *the force exerted by the liquid on the disc is equal to the weight of a column of water the base of which is the internal section of the tubulure, c, and the height the vertical distance from the disc to the surface of the liquid.*

This principle is sometimes called the *hydrostatical paradox*, for at first sight it seems quite impossible.

The pressure at great depths in the sea is very considerable. A corked empty bottle, when loaded to make it sink and lowered to a sufficient depth, is found when brought to the surface to be full of water, the pressure having forced the cork in. The bulbs of

thermometers for registering deep sea temperatures are provided with envelopes partially filled with the liquid (alcohol or mercury) of which the thermometer is made. Shellfish from great depths have shells which weigh as much as from one to two hundred pounds. Fish from the higher levels are killed when brought rapidly to lower depths, as is proved by experiments with the hydraulic press.

91. **Pascal's experiment.**—Pascal made the following experiment, which illustrates what great pressures may be produced by even small quantities of liquid when contained in vessels of great height. He fixed firmly in a stout cask, as represented in fig. 88, a very narrow tube about 30 feet in height, and then filled the cask and the tube with water. The effect of this was to burst the cask; for there was a pressure on the bottom of the cask equal to the weight of a column of water whose base was the bottom itself, and whose height was equal to that of the water in the tube.

92. **Hydraulic press.**—The law of the equal transmission of fluid pressure has received a most important application in the *hydraulic press*, a machine by which enormous pressures may be produced. Its principle is due to Pascal, but it was first constructed by Bramah in 1796.

Fig. 89 represents an elevation, and fig. 90 a section, of the apparatus; it consists of two iron cylinders or barrels, A and B, of unequal diameters. In the barrel A, which is of very small diameter, is a cylindrical rod, *a*, which acts as piston, and can be moved up and down by the lever O. In the cylinder B, the internal diameter of which is twelve to fifteen times that of the barrel A, is a long cylindrical iron ram, C, which also forms a piston, and works water-tight in the barrel B. On the top of the ram, C, is a thick iron slab, K, which rises and falls with it. Four wrought-iron columns support a second plate, MN, which is fixed. The objects to be pressed are placed between K and MN.

When the piston is raised by means of the lever, the pressure is diminished in the barrel A, and a valve, S, at the bottom opens and allows water to pass from a reservoir, P, into the barrel. When *a* re-descends, the valve, S, closes; but another valve, *m*, placed at the bottom of the tube *d*, opens; the water is thus forced by this tube into the large cylinder, B. At the next stroke of the piston, *a*, a fresh quantity of water is drawn from the reservoir, P, and forced into the barrel, B, and so forth.

In consequence of the principle of the equality of pressure, the

downward pressure exerted by the small piston, *a*, is transmitted upwards upon the piston C. The pressure which can be obtained depends on the relation between the size of the piston C and that of the piston *a*. If the former has a transverse section fifty or a hundred times as large as the latter, the upward pressure on the large piston will be fifty or a hundred times that exerted upon the small one (85). By means of the lever, O, an additional advantage

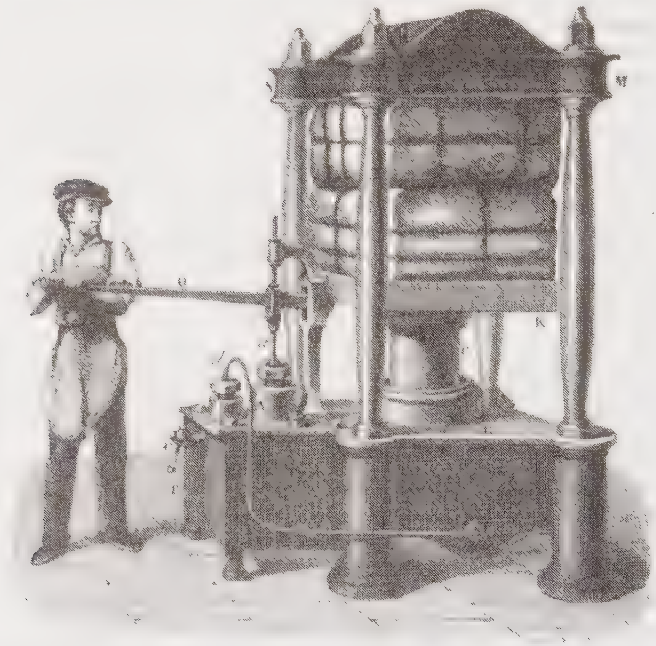


Fig 89.

is obtained. If the distance from the fulcrum to the point where the power is applied is five times the distance from the fulcrum to the piston *a*, the force on *a* will be five times that applied (35). Thus if a man acts on O with a force of 60 lb., the force transmitted by the piston *a* will be 300 lb., and the force which tends to raise the piston C will be 30,000 lb., supposing the section of C is a hundred times that of *a*.

The hydraulic press is used in nearly all cases in which great pressures are required. It is applied in compressing cloth, hay, cotton, gunpowder, and gun-cotton; in extracting the juice of beetroot, in expressing oil from seeds, and in pressing apples in making cider; in the extraction of stearine, and in flattening paper and cloth; it also serves to test the strength of cannon, of steam boilers, and of chain cables, to bend iron and steel plates for armour-clad vessels, and to press the spokes of wheels to the axis. The parts composing the tubular bridge which spans the Menai Straits were raised by means of a hydraulic press. The cylinder of this machine, one of the largest which has ever been constructed,

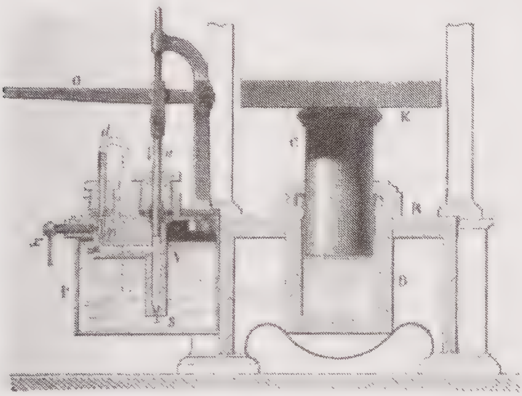


Fig. 90

was 9 feet long and 22 inches in internal diameter; it was capable of raising a weight of 2,000 tons.

The principle of the hydraulic press is also applied to the working of heavy cranes, windlasses, the opening of dock gates, and to *hydraulic lifts*, which are of such extensive use in large warehouses, hotels, and the like. It is even used in working stage machinery.

In these cases a hydraulic *accumulator* is used. The piston is loaded with very great weights, and water is continually forced into the cylinder by powerful pumps. From the bottom of this cylinder a tube conducts water to any place where the power is to be applied, and the flow of even small quantities of water which is under high pressure can perform a great amount of work. It is

thus applied with advantage to the transmission of power to a distance.

In London, water is supplied to consumers by the Hydraulic Power Company under a pressure of 700 lb. per sq. in.; and the quantity required for one horse-power would be about 175 gallons. The cost of power supplied in this way is about fourpence per horse-power per hour, which, although expensive for continuous working, is not so when it is intermittently used, and when only the quantity actually consumed is paid for.

CHAPTER II

EQUILIBRIUM OF LIQUIDS

93. **Conditions of the equilibrium of liquids.**—We have seen (47) that the condition of the equilibrium of a solid is that its centre of gravity be supported; all the other parts of the body then retain the same state of equilibrium, in consequence of cohesion, which unites the particles to each other and to the centre of gravity. This is by no means the case with liquids; owing to the great mobility of their molecules, and the facility with which they obey the force of gravity, they would fly away and spread out if they were not retained by some obstacle. Hence a liquid cannot be at rest in any vessel, unless it satisfies the following conditions :—

I. *The free surface of the liquid must be horizontal—that is, perpendicular everywhere to the direction of gravity.*

II. *Each molecule of the mass of the liquid must be subject in every direction to equal and contrary forces.*

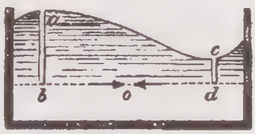


Fig. 91.

The second condition is self-evident; for if the forces exerted on any given particle, in two opposite directions, were not equal and contrary, the particle would be moved in the direction of the greater force, and there would be no equilibrium. Thus the second condition follows from the principle of the equality of pressures, and from the reaction which all pressure causes on the mass of liquids.

To account for the first condition, relative to the free surface of the liquid, let us observe that in a liquid whose surface is horizontal, all the particles supporting each other, the action of gravity is balanced, and the liquid is at rest. But if the surface is not horizontal, if some parts are higher than others (fig. 91), the highest part, *ab*, exerts upon any horizontal layer, *bd*, a greater pressure than the part *cd*, and therefore, since any given

particle, *o*, of the horizontal layer is exposed to a greater pressure in the direction *bo* than in the direction *do*, equilibrium is impossible.

In saying that for a mass of liquid to be in equilibrium its surface must be horizontal, we must remark that that presupposes the liquid to be only acted upon by gravity, which is usually the case; if it is under the action of other forces, for example, capillary forces (74), its surface is inclined so as to be perpendicular to the resultant of all the forces which act upon it.

94. **Level of liquids.**—A liquid is said to be *level* when all the points of its surface are in the same horizontal plane. This, how-

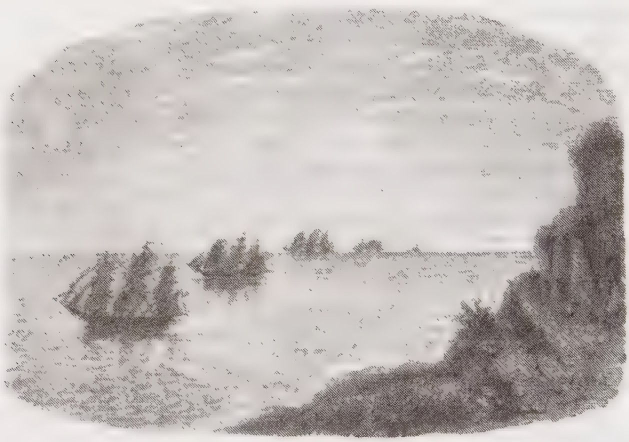


Fig. 92.

ever, only applies to surfaces of small extent. For, as the direction of the vertical constantly changes from one place to another on the surface of the globe, the directions of the horizontal surfaces change too—that is to say, a plane which is horizontal at one part of the earth's surface is not parallel to a horizontal plane at a small distance; they form a very small angle with each other. Hence a liquid surface of some extent in a state of equilibrium, being necessarily horizontal in each of its parts, does not form one single perfectly plane surface, but a series of plane surfaces inclined to each other; which of course produces a curved surface This curvature cannot,

however, be perceived on surfaces of small extent, as in water contained in a vessel; for the surface of such a liquid is so level that it reflects the rays of light like the most perfectly polished plane mirror. The curvature is, however, easily observed on large surfaces like those of the sea. For if this surface were perfectly level, a ship in sailing away from the shore would only cease to be visible in consequence of increasing distance, and the less apparent parts, the masts and the cordage, would disappear first. This, however, is not the case: the hull first sinks below the horizon, then the lower parts of the masts, and ultimately the top, as seen in fig. 92, thus proving the curvature of the surface of the sea.

95. **True and apparent level.**—When we consider a great body of water—the Mediterranean Sea, for instance—its surface is said to be level when all points of the surface are equidistant from the centre of the earth. This is the *true level*; while that level which is defined as having all the points of its surface in the same horizontal plane is the *apparent level*, the level for the eye. The true level only coincides with the apparent level when the liquid surfaces are very small. If the earth did not rotate about its own axis, the surface of all seas would form a true level; but, owing to the centrifugal force which results from its daily motion (31), the surface is heaped up at the equator, and the level is higher than at the poles.

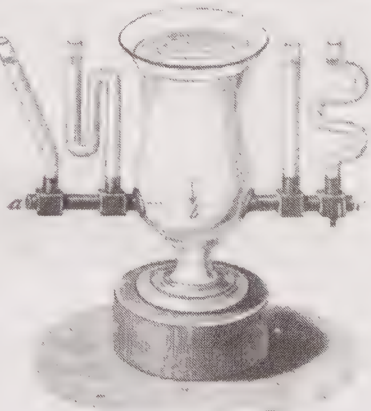


Fig. 93.

96. **Equilibrium of the same liquid in several communicating vessels.**—Not merely do liquids tend to become level when they are placed in the same vessel, but also when they are placed in vessels which communicate with each other. Whatever the shape and the dimensions of these vessels, equilibrium will exist *when the surfaces of the liquids in all the vessels are in the same horizontal plane.*

This principle may be demonstrated by means of the apparatus represented in fig. 93. It consists of a series of vessels of different shapes and capacities, connected together by a common horizontal tube. When water or any other liquid is poured into the vessel, the level is seen to rise at the same time, and to stop at exactly the same height in each. Equilibrium is then established. For we have seen that the pressures exerted by a liquid do not depend upon its quantity, but upon its height (90); when this is the same, the pressure is necessarily everywhere equal for all the vessels above the tube of communication *abc*, and therefore, as the liquid has no more tendency to flow from *b* towards *a* than from *b* to *c*, equilibrium continues. An ordinary tea or coffee pot is an illustration of this principle. The water stands at the same height in the spout as in the vessel itself.

97. **Equilibrium of different liquids in communicating vessels.**—In what has been said, the communicating vessels all contained the same liquid. It may, however, happen that the vessels contain liquids of different densities, which do not mix. The level is then no longer the same in both legs; the lighter liquids are higher, and equilibrium is only possible *when the heights of the liquid columns in communication, above the plane of their common surface, are inversely as their densities*—that is, if one of the liquids is twice or thrice as dense as another its height will be half or one-third as much.

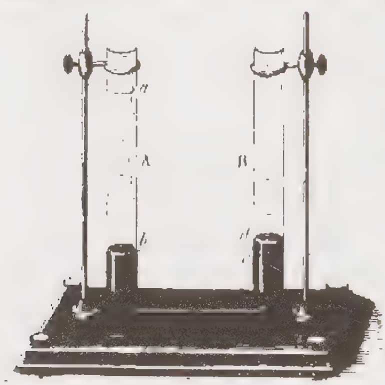


Fig. 94.

This principle is demonstrated experimentally by means of the apparatus represented in fig. 94. It consists of two glass tubes connected at the bottom by a narrow tube. The tubes are supported by two vertical columns, and on each of them is a scale graduated on the glass itself. If mercury is poured into one of the tubes it quickly assumes the same level in each. On now

pouring water into the tube A, the level of the mercury is seen to sink in this tube owing to the pressure of the water, and it rises in the other tube. Then, when equilibrium is established, the mercury in B is higher than in the tube A by a quantity *cd*. It is clear, then, that the pressure of the column of mercury, *cd*, counterbalances the pressure of the column of water *ab*. If now the heights of *ab* and *cd* be measured by means of the graduated scales on the two tubes, it will be found that the height *cd* is 13·6 times as small as that of *ab*; which demonstrates the above principle, for we shall presently learn that mercury is 13·6 times as heavy as water.

98. **Equilibrium of superposed liquids.**—In order that there should be equilibrium when several heterogeneous liquids which do not mix are superposed in the same vessel, each of them must satisfy the conditions necessary for a single liquid; and, further, *there will be stable equilibrium only when the liquids are arranged in the order of their decreasing densities, from the bottom upwards.*

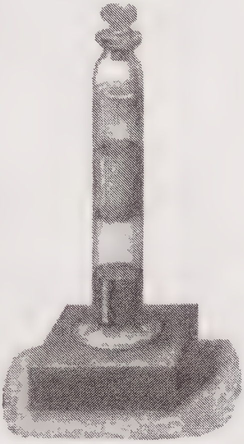


Fig. 95.

The last condition is experimentally demonstrated by means of a long narrow bottle (fig. 95) containing mercury, water saturated with potassium carbonate, alcohol coloured red, and petroleum. When the phial is shaken, the liquids mix; but when it is allowed to rest, they separate: the mercury sinks to the bottom, then comes the water, then the alcohol, and then the petroleum. This is the order of the decreasing densities of the bodies. The water is saturated with potassium carbonate to prevent its mixing with the alcohol.

This separation of the liquids is due to the same cause as that which enables solid bodies to float on the surface of a liquid of greater density than their own. In like manner, fresh water, at the mouths of rivers, floats for a long time on the denser salt water of the sea; the Gulf Stream (297) flows for a great distance owing to its smaller density; and, for the same reason, cream, which is lighter than milk, rises to the surface.

APPLICATIONS OF THE PRINCIPLE OF THE EQUILIBRIUM OF LIQUIDS

99. **Water level.**—In a great number of operations, such as the construction of canals, railways, roads, in laying drains, etc., it is frequently necessary to determine the difference in level of two more or less distant places. The simplest apparatus for this purpose is the *water level*, which is an application of the conditions of equilibrium in communicating vessels. It consists of a metal tube bent at both ends, in which are fitted glass tubes (fig. 96). It is placed on a tripod, and water poured in the tube until it rises in both limbs. When the liquid is at rest, the level of the water in both tubes is the same —that is, they are both in the same horizontal plane.

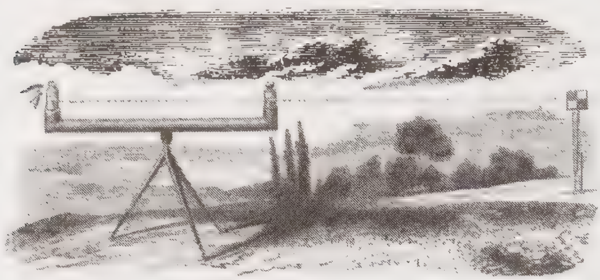


Fig. 96

This instrument may be used in *levelling*, or ascertaining how much one point is higher than another. If, for example, it is desired to find the difference between the heights of two places, a *levelling-staff* is fixed on the distant place. This staff consists of a rule formed of two sliding pieces of wood, one of which supports a piece of tin plate, in the centre of which there is a mark. This staff being held vertically, an observer looks at it through the level along the surfaces in the two tubes, and directs the holder to raise or lower the slide until the mark is in the line of the level in the two tubes. The assistant then reads off on the graduated rod the height of the mark above the ground. If this height exceeds that of the level, the height of the latter is subtracted from that of the former, and the difference gives the difference in the heights of the two places.

100. **Spirit level.**—The *spirit level* is both more delicate and

more accurate than the water level. It consists of a glass tube (fig. 97), very slightly curved ; it is filled with spirit with the exception of a bubble of air, which tends to occupy the highest part.

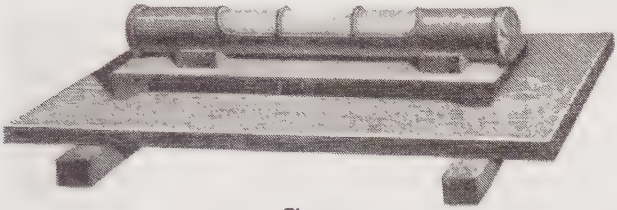


Fig. 97.

The tube is fixed in a brass case, which is so arranged that, when it is in a perfectly horizontal position, the bubble of air is exactly between the two points marked on the glass. But if the plane on which the instrument rests is ever so little inclined, the air-bubble tends to move towards the higher part. This, therefore, furnishes a ready means of ascertaining whether any article—a table, a stand, or a bookshelf—is quite horizontal in whatever position the level is laid.

For use in surveying the level is fixed on a special form or telescope on a stand, the apparatus being known as a dumpy level.

101. **Jets of water. Water supply.**—The sea, springs, rivers are all communicating vessels in which water tends to find its level. This is also the case with water jets.

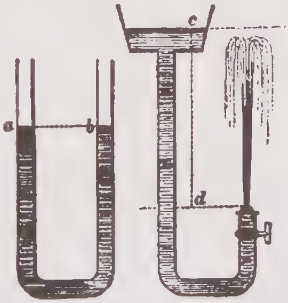


Fig. 98. Fig. 99.

Fig. 98 serves for the explanation of all the natural as well as artificial applications of the principle. If water is poured into one of the limbs of the U tube, the liquid rises in the other, and when they are at rest the level is the same in both. Suppose now that the limbs are of unequal length, the longer one being in connection with a reservoir of water, and the shorter one being provided with a stop-cock. If this is closed, and the liquid in the large branch is higher than the top

of the shorter branch by the length *cd*, the pressure on the stop-cock will be that due to the column *cd*. Hence if the stop-cock is opened the water issues in a vertical jet in consequence of this pressure (fig. 99). The jet ought to rise to the height *cd*, that is, to the level of the source; it does not quite reach this owing to the friction of water against the sides of the tube, to the resistance of the air, and to the particles which have risen falling on the jet.

The most important application of this kind is to the *water supply* of towns. Water from a reservoir at a great height, which is usually fed by brooks and springs, is led through iron pipes in any direction, and through depressions and over elevations, provided these latter are never higher than the source by which the pipes are fed. From the *mains*, as they are called, smaller pipes lead into the houses to be supplied.

102. **Streams, springs, wells.**—The formation of springs upon the surface of the earth, and in its interior, is also due to the tendency of water to seek its level. For gravity causes water to flow from higher to lower places. Hence it is that the rain which falls upon the earth, and the water arising from the melting of snow, pass down to the valleys, where they form brooks, streams, and rivers, which flow along their beds as along an inclined plane, until they emerge into the seas. A very small fall can give rise to a current. Thus the mean height of the Seine at Paris is not more than 35 yards above the level of the sea. The extent of its course between these two points is about 224 miles, which scarcely amounts to a fall of the $\frac{1}{3}\frac{}{3}$th part of an inch in a yard; and water requires several days to traverse this distance. The average fall of the Mississippi is 1 in 900, that of the Rhine between Mannheim and Mayence 1 in 7,400.

The rain which falls does not all flow upon the surface; part of it penetrates into the earth, and gives rise to small, subterranean watercourses, which are called *springs*. It is in order to procure water from these that *wells* are sunk.

103. **Artesian wells.**—When the spring which feeds a well comes from a place much higher than that where the well is sunk, it may happen that water tends to rise above the ground. This is the case in what are called *Artesian wells*. These wells derive their name from the province of Artois, where it has long been customary to dig them, and whence their use in other parts of France and Europe was derived. It seems, however, that, at a

very remote period, wells of the same kind were dug in China and Egypt.

The strata composing the earth's crust are of two kinds: the one *permeable* to water, such as sand, gravel, chalk, &c.; the other *impermeable*, such as clay. Let us suppose, then, a basin, H, of greater or less extent, in which the two impermeable layers AB, CD (fig. 100) inclose between them a permeable layer KK. The rainwater falling on the part of this layer which comes to the surface, which is called the *outcrop*, will filter through it, and, following the natural fall of the ground, will collect in the hollow of the basin, whence it cannot escape, owing to the impermeable strata above and below it. If now a vertical shaft, I, be sunk down to the water-bearing stratum, the water, striving to regain its level, will spout out to a height which depends on the difference

Fig. 100.

between the levels of the outcrop and of the point at which the boring is made.

The waters which feed Artesian wells often come from a distance of sixty or seventy miles. The depth varies in different places. The well at Grenelle is 1,800 feet deep; it gives 656 gallons of water in a minute, and is one of the deepest and most abundant which have been made. The temperature of the water is 27° C. It follows, from the law of the increase of temperature with the increasing depth below the surface of the ground (317), that, if this well were 210 feet deeper, the water would have all the year round a temperature of 32° C., which is the ordinary temperature of warm baths.

A well dug recently at Munden has a depth of 2,280 feet. In Algeria, and also in Australia, whole districts of desert have been converted into fruitful oases by means of Artesian wells. Thus on the Bateman Estate three boreholes have been sunk in a country which formerly supported a few head of cattle. One of these, at a depth of 1,500 feet, yields a flow of 2,900 gallons per minute, enough to supply water for 60,000 sheep. The two others yield an even larger supply.

CHAPTER III

PRESSURES SUPPORTED BY BODIES IMMERSED IN LIQUIDS. SPECIFIC GRAVITIES

104. **Pressure supported by a body immersed in a liquid.**—When a solid is immersed in a liquid, it is obvious that the pressures which the sides of the vessel support are also exerted against the surface of the body immersed, since liquids transmit pressure in all directions (85). But it is readily seen that the pressures which the immersed body supports do not neutralise themselves, but have a resultant, the tendency of which is to move the body upwards.

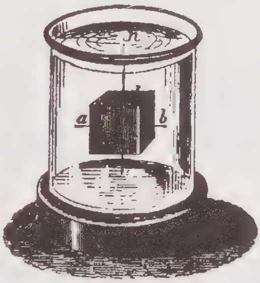


Fig. 101.

Let us imagine a cube immersed in a mass of water (fig. 101), and that four of its edges are vertical. The horizontal forces due to fluid pressure upon the two opposite faces, *a* and *b*, are clearly equal to each other, for they are exerted at the same depth (87); and as they are in opposite directions, they will balance one another, and the only effect will be to compress the body without displacing it.

But the vertical forces on the faces *d* and *c* are obviously unequal. The face *d* is pressed downwards by a column of water whose base is the face *d*, and whose height is *dn*; the lower face, *c*, is pressed upwards by the weight of a column of water whose base is the face itself, and whose height is *cn*. The cube, therefore, is urged upwards by a force equal to the difference between these two forces, which latter is manifestly equal to the weight of a column of water having the same base and the same height as this cube. By this reasoning, therefore, we arrive at the remarkable principle, that *any body immersed in a liquid is pressed upwards*

by a force equal to the weight of the volume of liquid which it displaces. We shall see how this principle can be experimentally verified.

105. **Principle of Archimedes. Hydrostatic balance.**—We have thus seen that any body immersed in a liquid is submitted to the action of two forces—gravity, which tends to make it sink, and the buoyancy of the liquid, which tends to raise it with a force equal to the weight of the liquid displaced. The body weighs less, therefore, than in air, and the diminution of its weight is exactly equal to the weight of the displaced liquid. The above principle may thus be enunciated: *a body immersed in a liquid loses a part of its weight equal to the weight of the displaced liquid.* For instance, suppose that a body which weighs 1,000 grains in air displaces a cubic inch of water when immersed in water; it will now only weigh 1,000 −252 = 748 grains (a cubic inch of water weighs 252 grains).

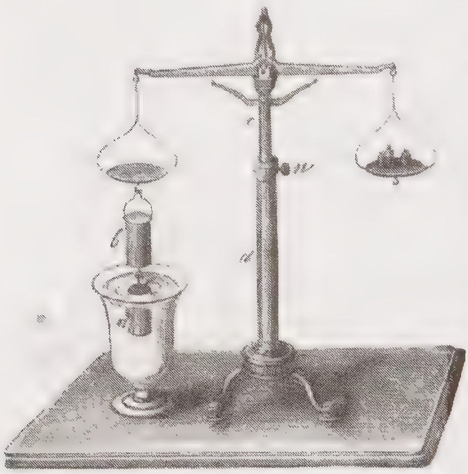


Fig. 102

This principle, which is remarkable for its numerous applications, is called the 'principle of Archimedes,' after the discoverer. It is shown experimentally by means of the *hydrostatic balance* (fig. 102). This is an ordinary balance, each pan of which is provided with a hook; the rod, *c*, slides in the hollow cylinder, *d*. The beam is supported on the rod, *c*, which can be fixed in any position by means of a screw, *n*. The beam being raised, a hollow brass cylinder, *b*, is suspended to one of the pans, and below this a solid cylinder, *a*, whose volume is exactly equal to the capacity of the first cylinder; lastly, an equipoise is placed in the other pan. If

now the hollow cylinder, *b*, be filled with water, the equilibrium is disturbed; but if, at the same time, the beam is lowered so that the solid cylinder *a* becomes immersed in a vessel of water placed beneath it, the equilibrium will be restored. By being immersed in water the cylinder *a* loses a part of its weight equal to that of the water in the cylinder *b*. Now, as the capacity of the cylinder *a* is exactly the same as that of the cylinder *b*, the principle which has been laid down is proved.

We have all had occasion to observe how much lighter our limbs appear in water, and, on the contrary, how much heavier they seem when lifted out. In like manner, if the body is almost entirely immersed in water, we can walk barefoot on the stones without injuring the feet; but this is not possible when we are out of the water. For in the former case part of the weight of the body is raised by the liquid, while in the latter the whole weight of the body presses the feet against the sharp projections. So, too, a man can raise a stone in water by means of a rope which he could not do in air.

106. **Equilibrium of immersed and floating bodies.**—When a body is placed in a liquid, three cases are possible: the body may have the same specific gravity as the liquid, in which case it weighs as much as the liquid for an equal volume; or it may be denser, in which case it weighs more; or it is lighter, and in this case it weighs less.

I. If the body immersed is of the same density as the liquid, the weight of the liquid displaced being the same as that of the body, it follows from Archimedes' principle that the buoyancy, which tends to raise it, is exactly equal to the force with which gravity tends to sink it. The two forces are thus in equilibrium, and the body remains in suspension in any position in liquid.

II. If the body immersed is denser than the liquid, it sinks, for then its weight preponderates over the buoyancy. This is the case when a stone or a mass of metal is thrown into water.

III. Lastly, if the immersed body is lighter than the liquid, the buoyancy prevails, and the body rises until it only displaces a weight of liquid equal to its own. It is then said to *float*. Cork, wax, wood, and all substances lighter than water, float on its surface. Iron floats on mercury.

In order to raise objects sunk in the sea, lighters are moored over them which are so full of water that they only just float, and which are connected with the objects by powerful chains. The

water is then pumped out of the lighter, and the buoyancy which is brought into play, by the substitution of air for water, exerts a steadily increasing, and ultimately enormous, pull on the immersed bodies.

The *erratic blocks* of granite and the like which are found far away from the formations to which they belong have been transported by icebergs in which they have been embedded. The buoyancy of *ground ice* may be so great as to lift stones and plants from the bottom.

A body which floats on one liquid may sink in another ; that this may happen, the body must be lighter than the one liquid, but heavier than the other. An egg sinks at once if placed in ordinary water, since it is heavier than an equal quantity of water ; but it swims if placed in strong brine, which is denser than water. A piece of oak floats on water, but sinks in ether, which is lighter than water. Iron floats on mercury, but sinks at once in water.

Fig. 103.

Yet a body, though denser than a liquid, may float on its surface. For this purpose it must have such a shape as to displace a volume of liquid the weight of which is greater than its own. Porcelain is much heavier than water, yet a porcelain saucer, placed on water, floats on the surface ; this arises from its concave shape, owing to which it displaces a weight of water equal to its own, though it is only partially immersed. For the same reason iron ships, even with very thick sides, float freely on water.

107. **Cartesian diver.**—The different effects of suspension, immersion, and floating are reproduced by means of a well-known hydrostatic toy, the *Cartesian diver* (fig. 103). It consists of a glass cylinder nearly full of water, on the top of which a brass cap, A, provided with a piston, is hermetically fitted. In the liquid there is a little porcelain figure—a fish, *o*, for example—attached to a

hollow glass ball, *m*, which contains air and water, and floats on the surface. In the lower part of this figure there is a little hole by which water can enter or escape, according as the air in the interior is more or less compressed. The quantity of water in the globe is such that very little more is required to make it sink. If the piston be slightly lowered, the air is compressed, and this pressure is transmitted to the water of the vessel and to the air in the bulb. The consequence is that, the air being compressed, a small quantity of water penetrates into the bulb, which therefore becomes heavier and sinks. If the pressure is relieved, the air in the bulb expands, expels the excess of water which has entered it, and the apparatus, being now lighter, rises to the surface. The experiment may also be made by replacing the brass cap and piston by a cover of sheet india rubber, which is tightly tied over the mouth. When this is pressed by the hand, the same effects are produced.

108. **Swimming bladder of fishes.**—Most fishes have an air-bladder below the spine, which is called the *swimming bladder*. The fish can compress or dilate this at pleasure by means of a muscular effort, and produce the same effects as those just described—that is, it can either rise or sink in water.

109. **Swimming.**—The human body is lighter, on the whole, than an equal volume of water ; it consequently floats on the surface,

Fig. 104.

and still better in sea water, which is heavier than fresh water. The difficulty in swimming consists, not so much in floating as in keeping the head above water, so as to breathe freely. In man the head is heavier than the lower parts, and consequently tends to sink ; and hence swimming is not natural to him, but is an art which requires to be learned. Quadrupeds, on the contrary, easily keep the head, which is less heavy than the hinder part

of the body, above water, and these animals therefore swim naturally.

If a person who cannot swim, and who falls into the water, could retain sufficient coolness to turn on his back, so that his face is out of water, he could breathe freely, and wait until help arrives. Instead of this, however, he generally attempts to raise his arms out of water, as if grasping at some fixed support. This is very dangerous ; for, as the arms no longer displace a quantity of liquid equal to their own bulk, their weight is not diminished to that extent, but concurs with that of the head in making him sink.

Weight for weight, fat persons float more easily than lean ones, for they displace more water. For the same reason air-bladders, or cork girdles, known as *safety belts*, are fastened to persons who are learning to swim (fig. 104), for then, without any considerable increase of weight, they displace more water, which increases the buoyancy and keeps them up.

Several kinds of birds, such as ducks, geese, and swans, swim easily on water. They owe this property to a thick coating of a light down, impervious to water, which covers the lower part of the body, so that even with a small immersion they displace a weight equal to their own.

SPECIFIC GRAVITY. HYDROMETERS

110. **Specific gravity.**—Daily experience shows us that different substances have very unequal weights for one and the same volume. For instance, we all know that gold weighs more than silver, lead than iron, stone than wood. In order to compare equal volumes of various substances as to their weights, the weight of water has been taken as a standard of comparison. For water is everywhere met with, and can always be had pure ; this latter condition is necessary, for the weight of a given volume of water differs with the substances it holds in solution. As, moreover, the weight varies with the temperature, a constant temperature must be adopted. Hence the standard is taken to be *distilled* water at a temperature of 4° C., for at this point, as we shall afterwards see (244), water has its greatest density.

The specific gravity of a substance is the weight of any volume of it compared with the weight of the same volume of distilled water at 4° C. When we say, therefore, that the specific gravity of gold is 19, and that of lead 11, we mean that the former metal is 19 times, and the latter 11 times, as heavy as water at 4° C.

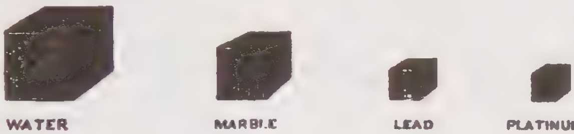


Fig. 105.

In order to get a clearer conception of the relative volumes of equal weights of different bodies, let us imagine that the square within which this portion of the text is inclosed represents the side of a cube of air; then the volumes of equal weights of water, marble, lead, and platinum will be represented by the corresponding cubes.

111. **Determination of the specific gravity of solids.**—Three methods are commonly used in determining the specific gravities of solids and liquids. These are—the method of the hydrostatic balance, that of the hydrometer, and that of the specific gravity flask. All three, however, depend on the same principle—that of first ascertaining the weight of a body, and then that of an equal volume of water. We shall apply these methods to determining the specific gravity first of solids, and then of liquids.

Hydrostatic balance.—To obtain the specific gravity of a solid—a piece of iron, for instance—by means of the hydrostatic balance (fig. 106) the iron is first weighed in air by suspending it to the hook of one of the pans. Let us suppose that its weight is 585 grains. It is then weighed while immersed in distilled water, as shown in fig. 106. It will now weigh less; suppose the weight to be 510 grains, this is in accordance with Archimedes' principle, for it now loses a weight equal to that of the water which it displaces. Hence, subtracting 510 from 585, the difference 75 represents the

weight of the displaced water—that is, the weight of a volume of water equal to that of the iron. We need now only calculate how often the weight 75, that of the water, is contained in 585, that of the iron, and the quotient, 7·8, is the specific gravity of iron; it says that, for equal volumes, this substance weighs 7·8 times as much as water.

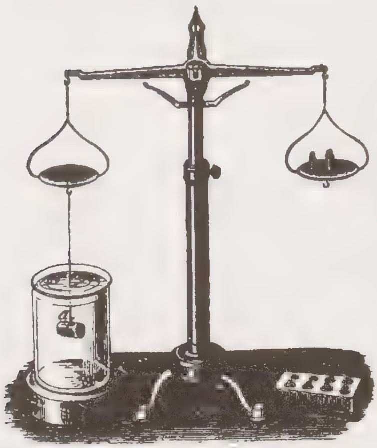


Fig. 106.

Nicholson's hydrometer.—This apparatus consists of a hollow metal cylinder (fig. 107), to which is fixed a cone, *d*, loaded with lead. The object of the latter is to lower the centre of gravity so that the cylinder maintains the vertical position when in the water. At the top is a stem, *c*, terminated by a pan, *a*, on which is placed the substance whose specific gravity is to be determined. On the stem a standard point, *c*, is marked.

The apparatus stands partly out of the water, and the first step is to ascertain the weight which must be placed in the pan in order to make the hydrometer sink to the standard point, *c* (fig. 108). Let this weight be 125 grains, and let sulphur be the substance whose specific gravity is to be determined. The weights are then removed from the pan, and replaced by a piece of sulphur which weighs less than 125 grains, and weights added until the hydrometer is again depressed to the mark, *c*. If, for instance, it has been necessary to add 55 grains, the weight of the sulphur is evidently the difference between 125 and 55 grains, that is, 70 grains.

Having thus determined the weight of the sulphur in air, it is now only necessary to ascertain the weight of an equal volume in water. To do this, the piece of sulphur is placed in the lower pan at *d*, as represented in fig. 109. The whole weight is not changed, nevertheless the hydrometer no longer sinks to the standard point: the sulphur, by immersion, has lost a part of its weight equal to that

of the water displaced. Weights are added to the upper pan until the hydrometer sinks again to the standard. This weight—34·4 grains, for example—being the difference between the weight of the sulphur in air and its weight in water, represents the weight of the volume of water displaced : that is, of the volume of water equal to the volume of the sulphur.

It is only necessary, therefore, to divide 70 grains, the weight in air, by 34·4 grains, and the quotient, 2·03, is the specific gravity sought.

Specific gravity flask.—In this method, which is advantageously used for the determination of the specific gravity of bodies in a

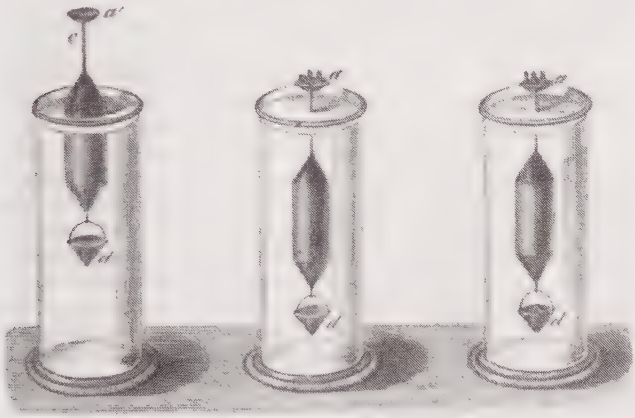


Fig. 107. Fig. 108. Fig. 109.

state of powder, a wide-necked bottle is selected which can be carefully closed by a ground-glass disc (fig. 110). When filled with water, it is closed with the disc, great care being taken that not a bubble of air is left. After being carefully wiped dry, it is placed in the pan of a balance, and by its side is the substance, *a*, whose specific gravity is to be determined. The whole is then equipoised by weights placed in the other pan of the balance. The substance, *a*, is then removed, and weights added in its place, until equilibrium is again established. The weight necessary for this purpose gives the weight of the substance in air.

The substance is now placed in the flask, and displaces some

of the water ; the disc is adjusted, and the whole again carefully wiped dry. In order to equipoise the tare in the second pan, weights must now be added on the side of the flask to make up for the water displaced. The weights necessary for this purpose represent then the weight of a volume of water equal to that of the body.

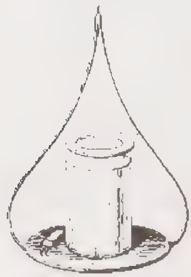


Fig. 110.

Dividing, then, the weight of the body in air by the weight of an equal volume of water, we have the specific gravity sought.

112. **Specific gravity of liquids.**—These are determined by the same methods as those of solids.

Hydrostatic balance.—In determining the specific gravity of a liquid by this means, a body is suspended to one of the pans of the balance, which is neither dissolved by the liquid whose specific gravity is to be determined, nor by water ; for instance, a ball of platinum, which is insoluble in all ordinary liquids. This ball is first weighed in air, then in water, and finally in the liquid in question, which we will suppose is alcohol. Let us assume that the ball weighs 510 grains in air, in water 486 grains, and in alcohol 489 grains. The loss of weight in water has thus been 510 less 486, or 24 grains, and in alcohol 510 less 489, or 21 grains ; which tells us that if a volume of water equal to that of the ball weighs 24 grains, the same volume of alcohol weighs 21 grains. Hence, to obtain the specific weight of alcohol we must ascertain the number which expresses the ratio 21 to 24, which of course is obtained by division. The quotient is 0·866, which represents the specific gravity of alcohol as compared with water.

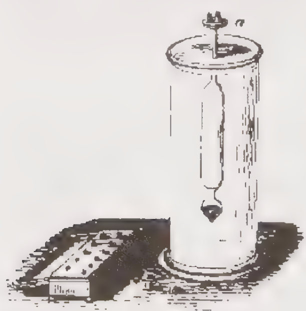


Fig. 111.

Fahrenheit's hydrometer.—This instrument (fig. 111) resembles Nicholson's hydrometer, but it is made of glass, so as to be used in all liquids. At its lower extremity, instead of a pan,

it is loaded with a small bulb containing mercury. There is a standard mark on the stem, at the top of which is a pan.

The weight of the instrument is first accurately determined in air by means of an ordinary balance. Let us suppose that its weight is 618 grains, and that the liquid whose specific gravity is to be determined is olive oil. The hydrometer is placed in water, and the pan, *a*, is loaded with weights, until the liquid is level with the mark on the stem. Suppose it has been necessary to add 93 grains for this purpose ; these 93 grains, together with the 618 which the instrument weighs, make 711 grains, which represent the weight of water displaced by the instrument (106). The hydrometer is then removed, wiped dry, and immersed in the olive oil. Let us suppose that now only 31 grains need be added to sink the hydrometer to the mark. These, together with the 618 grains which the instrument weighs, in all 649, represent the weight of the displaced oil. We thus learn that equal volumes of oil and water weigh respectively 649 and 711. Hence we obtain the specific gravity of the latter as compared with the former by dividing 649 by 711. The quotient is 0·91, which teaches us that if a certain volume of water weighs 100 grains, the same volume of oil weighs 91 grains.

Neither Fahrenheit's nor Nicholson's hydrometers give such accurate results as the specific gravity bottle.

Specific gravity bottle.—This consists of a cylindrical reservoir, *b* (fig. 112), to which is fused a narrow tube, *c*, and to this again a wider one, *a*, closed by a stopper. In determining the specific gravity of a liquid, the bottle is first weighed empty, and then,

Fig. 112.

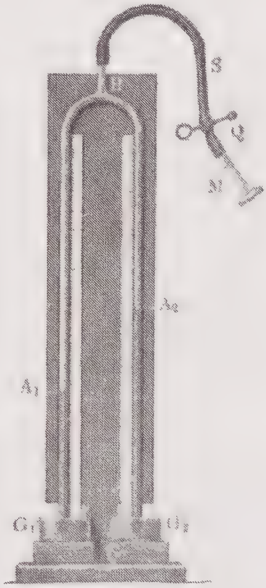


Fig. 113.

successively, full of water and of the given liquid to the mark *c*. If the weight of the empty bottle be subtracted from the two weights thus obtained, the result represents the weights of equal volumes of water and of the liquid under experiment, from which the specific gravity is obtained by division.

An interesting method of comparing the specific gravities of liquids is represented in fig. 113, in which B is a three-way tube, provided with an india rubber tube and a mouthpiece. One of the ends, A_1, being placed in a standard liquid, G_1, water, for example, the other, A_2, is placed in the liquid to be examined. By suction the liquids are raised in the two tubes, and by means of a clip the tube S is closed, and the heights in the two tubes above the surface of the liquids in G_1, G_2 read off; the experiment is repeated several times, and the means of the respective heights taken. They will be inversely as the specific gravities.

Specific gravities of solids

Platinum	22·07	Salt	2·22
Gold	19·36	Anthracite	1·80
Lead	11·35	Coal	1·32
Silver	10·47	Amber	1·07
Copper	8·87	Ice at 0° C.	0·93
Bronze coinage	8·66	Oak	0·84
Iron	7·78	Yellow pine	0·65
Zinc	6·86	Common poplar	0·38
Diamond	3·53	Cork	0·24
Statuary marble	2·83	Snow	0·18
Aluminium	2·68	Pith	0·07
Glass	2·48		

Specific gravities of liquids

Mercury	13·60	Distilled water at 0° C.	0·99
Methylene iodide	3·34	Claret	0·99
Bromine	2·96	Olive oil	0·91
Sulphuric acid	1·84	Liquid oxygen	0·89
Glycerine	1·26	Oil of turpentine	0·87
Milk	1·03	Absolute alcohol	0·80
Sea water	1·02	Ether	0·72
Distilled water at 4° C.	1·00	Pentane	0·62

113. **Use of tables of specific gravities.**—Tables of specific gravities admit of numerous applications. In mineralogy the specific gravity of a mineral is often a highly distinctive characteristic. Jewellers also use them. By means of tables of specific gravities the weight of a body may be calculated when its volume is known, and, conversely, the volume when its weight is known.

With a view to explaining the last-mentioned use of these tables, it will be well to state the connection existing between the British *units of length, capacity, and weight*. It will be sufficient for this purpose to define that which exists between the *yard*, *gallon*, and *pound avoirdupois*, since other measures stand to these in well-known relations. The yard, consisting of 36 inches, may be regarded as the primary unit. The gallon contains 277·274 cubic inches. A gallon of distilled water at the standard temperature weighs 10 lb. avoirdupois, or 70,000 grains troy; or, which comes to the same thing, one cubic inch of water weighs 252·5 grains.

On the French or what is called the *metric* system the *metre* is the primary unit, and is so chosen that 10,000,000 metres are the length of a quadrant of the meridian from either pole to the equator. The metre contains 10 decimetres, 100 centimetres, or 1,000 millimetres; its length equals 1·0936 of a yard, or 39·37 inches. It is about a quarter of an inch longer than a pendulum which in this latitude beats seconds (65). The unit of the measure of capacity is the *litre* or cubic decimetre. The unit of weight is the *gramme*, which is the weight of a cubic centimetre of distilled water at 4° C. The kilogramme contains 1,000 grammes, or is the weight of a decimetre of distilled water at 4° C. The gramme equals 15·432 grains.

Suppose it is required to calculate the weight of a cubic foot o. coal. A cubic foot contains 1,728 cubic inches; the weight of a cubic foot of water would therefore be 1,728 times 252·5 grains. This product divided by 7,000 (the number of grains contained in a pound avoirdupois) gives 62·3 lb. as the weight of a cubic foot of water; and as we learn from the tables that coal is 1·32 times as heavy as water, the weight of a cubic foot of coal will be 1·32 times 62·3, or 83·16 lbs.

114. **Hydrometers.**—The hydrometers of Nicholson and Fahrenheit are called *hydrometers of constant immersion but variable weight*, because they are always immersed to the same

depth, but carry different weights. There are also ***hydrometers of variable immersion but of constant weight***, known under the different names of *acidometer*, *alcoholometer*, *lactometer*, and *saccharometer*.

115. **Beaumé's hydrometer.**—This, which was the first of these instruments, may serve as a type of them. It consists of a glass tube, AB (fig. 114), loaded at its lower end with mercury, and with a bulb blown in the middle. The stem, the external diameter of which is as regular as possible, is hollow, and the scale is marked upon it.

The graduation of the instrument differs according as the liquid for which it is to be used is heavier or lighter than water. In the former case it is so constructed that it sinks in water nearly to the top of the stem, to a point, A, which is marked zero. A solution of fifteen parts by weight of salt in eighty-five parts of water is made, and the instrument immersed in it. It sinks to a certain point on the stem, B, which is marked 15; the distance between A and B is divided into 15 equal parts, and the graduation continued to the bottom of the stem. Sometimes the graduation is on a piece of paper in the interior of the stem.

Fig. 114.

The hydrometer thus graduated only serves for liquids of greater specific gravity than water, such as acids and saline solutions. For liquids lighter than water a different plan must be adopted. Beaumé took for zero the point to which the apparatus sank in a solution of 10 parts of salt in 90 of water, and for the graduation 10 he took the level in distilled water. This distance he divided into ten equal parts, and continued the division to the top of the scale.

The graduation of these hydrometers is entirely arbitrary, and they give neither the exact densities of the liquids nor the quantities dissolved. But they are very useful in making mixtures or solutions in given proportions; the results they give being sufficiently near in the majority of cases. For instance, it is found that a well-made syrup marks 35° on Beaumé's hydrometer, from which a manufacturer can readily judge whether a syrup which is being evaporated has reached the proper degree of concentration.

116. **Gay-Lussac's alcoholometer.**—The spirits of wine and

the brandy in daily use are essentially a mixture of pure alcohol and water. The more alcohol they contain, the stronger they are; the more water they contain, so much the weaker are they. Hence it is important to have a simple means of exactly determining the quantity of water contained in spirituous liquors. This is effected by means of Gay-Lussac's *alcoholometer*, which has the same shape as Beaumé's, and only differs in the graduation. This is effected as follows :—

Mixtures of absolute alcohol and distilled water are made, containing 5, 10, 20, 30, &c. per cent. of the former. The alcoholometer is so constructed that, when placed in pure distilled water, the bottom of its stem is level with the water, and this point is zero. It is next placed in absolute alcohol, which marks 100, and then successively in mixtures of different strengths, containing 10, 20, 30, &c. per cent. The divisions thus obtained are not exactly equal, but their difference is not great, and they are subdivided into ten divisions, each of which marks *one* per cent. of absolute alcohol in a liquid. Thus a brandy in which the alcoholometer stood at 48 would contain 48 per cent. of absolute alcohol, and the rest would be water.

All these determinations are made at 15° C., and for that temperature only are the indications correct. For, other things being the same, if the temperature rises, the liquid expands, and the alcoholometer will sink ; and the contrary if the temperature falls. To obviate this error Gay-Lussac constructed a table which for each percentage of alcohol gives the reading of the instrument for each degree of temperature from 0° up to 30°. When the exact analysis of an alcoholic mixture is to be made, the temperature of the liquid is first determined, and then the point to which the alcoholometer sinks in it. The number in the table corresponding to these data indicates the percentage of alcohol. From its giving the percentage of alcohol this is often called the *centesimal alcoholometer*.

Twaddell's hydrometer is in common use in England for liquids denser than water. It is graduated so that the reading or number of degrees multiplied by 5 and added to 1000 gives the specific gravity referred to water as 1000. Thus 10° Twaddell represents the specific gravity 1050, and 90° represents 1450.

117. **Lactometer.**—The lactometer A is a form of hydrometer especially graduated for the purpose of ascertaining the quality of milk (fig. 115). This is accomplished in the following manner.

The instrument is immersed in a vessel containing pure milk, the average density of which is 1·0322, and the point to which it sinks is marked zero on a paper strip affixed to the stem. Mixtures are then made of $\frac{9}{10}$ of pure milk and $\frac{1}{10}$ of water; of $\frac{8}{10}$ and $\frac{2}{10}$, and so on to $\frac{5}{10}$ of milk and $\frac{5}{10}$ of water. The lactometer is successively immersed in these, and sinks to different depths; the point at which it stops in each case is marked by a number on the stem, and thus indicates a milk of a particular strength—that is, one containing a certain quantity of admixed water.

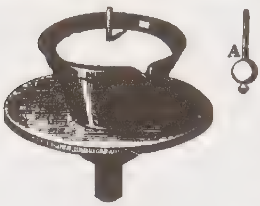


Fig. 115.

The lactometer is, however, no infallible test for the intentional adulteration of milk; for the density of natural milk is subject to variation, and an apparent fraud may really be due to a bad natural quality of milk.

BOOK III

ON GASES

CHAPTER I

PROPERTIES OF GASES. ATMOSPHERE. BAROMETERS

118. **Physical properties of gases.**—Gases, as we have already seen (7), are bodies which neither have form of their own, like solids, nor assume the shape of the containing vessel, like liquids, but are continually tending to occupy a greater space. This property of gases is known by the names *expansibility*, *tension*, or *elastic force*, from which they are often called *elastic fluids*.

The number of gases with which chemistry makes us acquainted is very considerable; but comparatively few are elementary, of which the principal are oxygen, hydrogen, nitrogen, and chlorine. Some gases are coloured, but most of them are colourless. Some have a disagreeable odour, others are quite inodorous. Some are noxious, acting as poison to men and animals which breathe them: such are carbonic oxide, which is produced by the combustion of charcoal; sulphuretted hydrogen, which is given off from drains. Others are inoffensive, such as nitrogen and hydrogen; yet an animal cannot live in them. They are not deleterious in the sense of being poisonous; but they do not support life. The only gas which has this property is oxygen; an animal deprived of this gas, even for a short time, soon dies.

Gases and liquids have several properties in common, and some in which they seem to differ are in reality only different degrees of the same property. Thus, in both the particles are capable of moving: in gases quite freely; in liquids not quite freely, owing to a certain degree of viscosity. Both are compressible, though in very different degrees: if a liquid and a gas both exist under a

pressure of one atmosphere, and then the pressure be doubled, the water is compressed by about the $\frac{1}{20000}$th part (84), while the gas is compressed by one-half. In density there is great difference; water, which is the type of liquids, is about 770 times as heavy as air, the type of gaseous bodies, while under a pressure of one atmosphere. The property by which gases are distinguished from liquids is their tendency to indefinite expansion.

By the aid of pressure and of very low temperatures, the force of cohesion may be so far increased in gases that they are converted into liquids. On the other hand, heat, which forces the particles farther apart, converts liquids, such as water, alcohol, and ether, into the aëriform state, in which they obey all the laws of gases. This aëriform state into which liquid may pass is known by the name of *vapour*, while *gases* are bodies which, under ordinary changes of temperature and pressure, remain in the aëriform state.

In describing the properties of gases we shall, for obvious reasons, have exclusive reference to atmospheric air as their type.

119. **Atmospheric air.**—Air is the gaseous fluid in which we live. It was regarded by the ancients as one of the four elements. Modern chemistry, however, has shown that it is a mixture of oxygen and nitrogen gases in the proportion of 20·8 volumes of the former to 79·2 volumes of the latter. By weight it consists of 23 parts of oxygen to 77 parts of nitrogen.

The oxygen feeds all the combustions which are produced round about us; and it also supports animal life. If it alone were present, or even if it were present in a larger proportion, combustion would be too brisk, and life too active. The inert properties of the nitrogen attenuate the too powerful effects of the oxygen. Air contains also a small percentage of *argon*, an inert gas like nitrogen, and still smaller percentages of other gases, named by Sir Wm. Ramsay, their discoverer, *neon*, *krypton*, and *xenon*.

Air is inodorous, transparent, and colourless, at any rate in small masses. In larger masses it is blue; thus arises the blue colour of the sky. Without air the sky would appear black; it appears almost so when viewed from the tops of very high mountains, and from balloons; for then the air above is very highly rarefied.

Air too, in virtue of its elasticity, is the medium for transmitting sounds; so that, if we were without it, the use of speech and of music would be lost.

120. **Expansibility of gases.**—This property of gases, their tendency to assume continually a greater volume, is exhibited by means of the following experiment. A bladder closed by a stopcock, moistened so as to render it more flexible, and about half full of air, is placed under the receiver of the air-pump (fig. 116), and a partial vacuum is produced, on which the bladder immediately distends. A spiral spring only exhibits elasticity when it is compressed ; it loses its elastic force when it has regained its original form. Gases have a continual tendency to expand ; they have no primitive volume, but, however rarefied, they always tend to occupy a continually greater space. Before the pump is worked the pressure inside the bladder is counterbalanced by the air in the receiver, which exerts an equal and contrary pressure. But when, by the action of the pump, this pressure is diminished, the internal pressure becomes evident. When air is again admitted into the receiver, the bladder resumes its original form. The same effects would be produced whatever gases were contained in the bladder, thus showing that all are expansible.

Fig. 116.

121. **Weight of gases.**—From their extreme fluidity and expansibility, gases seem to be uninfluenced by the force of gravity ; they nevertheless possess weight, like solids and liquids. To show this, a glass globe of 3 or 4 quarts capacity is taken (fig. 117), the neck of which is provided with a stopcock, which hermetically closes it, and by which it can be screwed to the plate of the air-pump. The globe is then exhausted as far as possible, and its weight determined by means of a delicate balance. Air is now allowed to enter, and the globe again weighed. The weight in the second case will be found to be greater than before, and, if the capacity of the vessel is known, the increase will obviously be the weight of that volume of air.

Fig. 117.

By a modification of this method, and with the adoption of certain precautions, the weight of air and of other gases has been determined (247). 100 cubic inches of dry air under the ordinary atmospheric pressure of 30 inches and at the temperature of 16° C.

weigh 31 grains; the same volume of carbonic acid gas under the same conditions weighs 47·25 grains; 100 cubic inches of hydrogen, the lightest of all gases, weigh 2·14 grains; and 100 cubic inches of hydriodic acid gas weigh 146 grains.

The ratio of the density of air at 0° C. and 30 inches pressure to that of water at 0° C. is found to be as 0·001293 is to 1. In other words, the latter is about 773 times as heavy as the former.

122. **The atmosphere. Experiments proving its weight.**—The *atmosphere* is the name given to the layer of air which, like a light coating, surrounds our globe in every part. It shares the rotatory motion of the globe (31, 33), and would remain fixed relatively to terrestrial objects but for local circumstances, which produce winds, and are constantly disturbing its equilibrium.

Besides the oxygen, nitrogen, and argon of which the air is composed, there is always present a quantity of aqueous vapour, which varies with the temperature, the season, the locality, and the direction of the winds. The mean amount of this in London is from 5 to 6 grains in a cubic foot of air.

It further contains from 3 to 6 parts in 10,000 of carbonic acid. This arises from the respiration of man and animals, from the decay of organic matter, and from the combustion of wood and coal. This latter cause of the production of carbonic acid increases every year. It has been calculated that in Europe alone about 104 milliards of cubic yards of carbonic acid are every year sent into the atmosphere from this source. This mass of gas is equal to what would be produced by 500 millions of individuals, each by the act of respiration converting 154 grains of carbon into carbonic acid every hour.

Notwithstanding this enormous continual production of carbonic acid on the surface of the globe, the composition of the atmosphere remains practically constant; for plants in the process of growth decompose the carbonic acid, assimilating the carbon, and restoring to the atmosphere the oxygen which is being continually consumed in the processes of respiration and combustion. Thus by a natural harmony, the atmosphere retains an almost uniform quantity of this gas, so that there seems no fear of its accumulating to such an extent as to be injurious to the human race. The question as to the exact height of the atmosphere must be considered as still awaiting settlement.

123. **Atmospheric pressure.**—Having seen that air has weight, it is easy to conceive that the enormous mass of air which constitutes

the atmosphere must exert a great pressure on the surface of the earth, and on all bodies found there. This pressure is called the *atmospheric pressure*. It necessarily decreases as we ascend in the atmosphere ; for if we conceive the atmosphere resolved into horizontal layers superposed on each other, it is clear that the lower layers which support the weight of the whole atmosphere are the most compressed and the most dense ; while the higher layers are less and less compressed, and therefore less and less dense. This is expressed by saying that they are more *rarefied* or more *rare*. In saying that 100 cubic inches of air weighed 31 grains, it was understood that air at the sea-level was referred to ; at any greater height this volume of air would weigh less.

The pressure of the atmosphere may be demonstrated by a number of experiments, among which are the following :—

124. **Crushing force of the atmosphere.**—On one end of a stout glass cylinder, about 5 inches high, and open at both ends, a piece of bladder is tied quite air-tight. The other end, the edge of which is ground and well greased, is pressed on the plate of the air-pump (fig. 118). The bladder is pressed downwards by the weight of the atmosphere, and is pressed upwards by the expansive force of the air in the cylinder. These two pressures at first counterbalance each other—the bladder is equally pressed on both sides ; but as soon as the internal air is removed from the vessel, by the action of the air-pump, the bladder is depressed by the weight of the atmosphere above it, and finally bursts with a loud report, caused by the sudden entrance of the air.

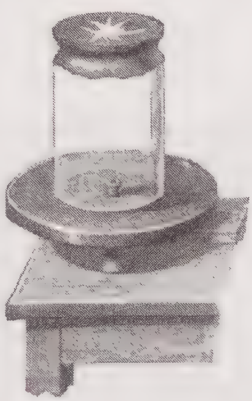


Fig. 118.

125. **Magdeburg hemispheres.**—The preceding experiment only serves to illustrate the downward pressure of the atmosphere. By means of the *Magdeburg hemispheres* (fig. 119), invented by Otto von Guericke, burgomaster of Magdeburg, it can be shown that the pressure acts in all directions. This apparatus consists of two hollow brass hemispheres of 4 to 4½ inches diameter, the edges of which are made to fit tightly, and are well greased. One of the hemispheres is provided with a stopcock and a short neck, by

which it can be screwed on the air-pump, and on the other there is a handle. As long as the hemispheres contain air they can be separated without any difficulty, for the external pressure of the atmosphere is counterbalanced by the pressure of the air in the interior. But when the air in the interior is pumped out by means of the air-pump, the hemispheres cannot be separated without a powerful effort (fig. 120); and as this is the case in whatever position they are held, it follows that the atmospheric pressure is exerted in all directions.

Fig. 119.

We shall presently see (128) that the pressure of the atmosphere on a square inch is equal to that of a weight which, in round numbers, may be taken at 15 lb. Hence if, in the above experiment, the area, not of each of the hemispheres, but of the circle along which they are pressed, is 10 square inches, the force by which they are pressed together is 150 lb., and this force would be required to separate them.

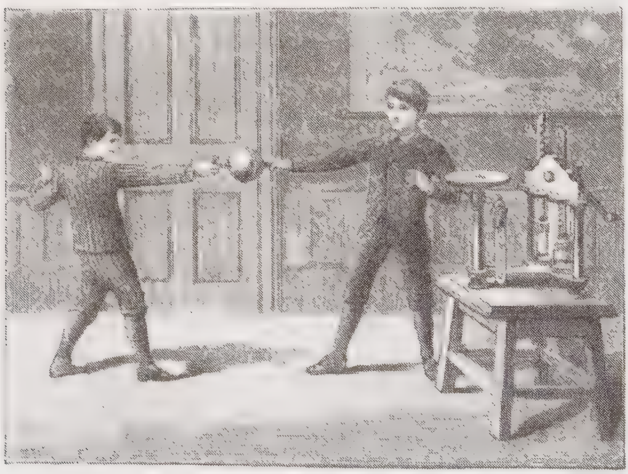


Fig. 120

Otto von Guericke, the inventor of this apparatus, constructed hemispheres the internal diameter of which was about 2 feet; when

applied against each other and exhausted, twelve horses, six pulling at each hemisphere, were required to separate them. This experiment was made at the Diet at Regensburg in 1654.

DETERMINATION OF THE ATMOSPHERIC PRESSURE. BAROMETERS

126. **Torricelli's experiment.**—The above experiments demonstrate the existence of atmospheric pressure, but they give no indications as to its amount. The following experiment, which was first made in 1643 by Torricelli, a pupil of Galileo, not merely proves the pressure of the atmosphere, but also gives an exact measure of its amount.

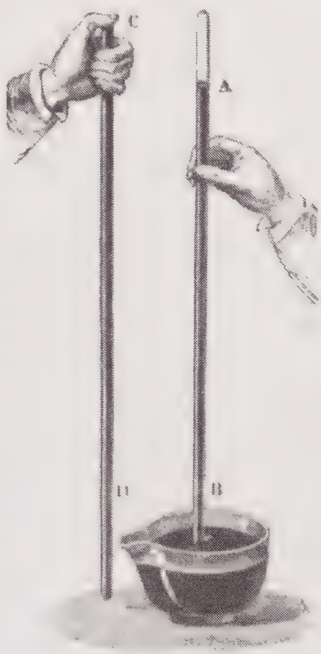


Fig. 121.

A glass tube C D is taken, about a yard long and a quarter of an inch internal diameter (fig. 121). It is sealed at one end, and is quite filled with mercury. The aperture C being closed by the thumb, the tube is inverted, the open end placed in a small mercury trough, and the thumb removed. The tube being in a vertical position, the column of mercury sinks, and after oscillating some time, it finally comes to rest at a height, A, which at the level of the sea is about 30 inches above the mercury in the trough. The mercury is raised in the tube by the pressure of the atmosphere on the mercury in the trough. There is no opposing pressure inside the tube on the mercury, because it is closed. But if the end of the tube be opened, the atmosphere will press equally inside and outside the tube, and the mercury will sink to the level of that in the trough. It has been shown (97) that the heights of two columns of liquid in communication with each

other are inversely as their densities ; and hence it follows that the pressure of the atmosphere is equal to that of a column of mercury, the height of which is 30 inches. That the mercury sank in the first case was due to its weight being greater than the pressure of the atmosphere. If, however, the pressure of the atmosphere diminishes, the height of the column which it can sustain must also diminish.

127. **Pascal's experiments.**—Pascal, who wished to prove that the cause of the suspension of the mercury in the tube was really the pressure of the atmosphere, made the following experiments :—i. If it were the case, he reasoned, the column of mercury ought to descend in proportion as we ascend in the atmosphere (123). He accordingly requested one of his relatives to repeat Torricelli's experiment on the summit of the Puy de Dôme in Auvergne. This was done, and it was found that the mercurial column was about 3 inches lower there, thus proving that it is really the weight of the atmosphere which supports the mercury, since, when this weight diminishes, the height of the column also diminishes. ii. Pascal repeated Torricelli's experiment at Rouen, in 1646, with other liquids. He took a tube closed at one end, nearly 40 feet long, and, having filled it with water, placed it vertically in a vessel of water, and found that the water stood in the tube at a height of 34 feet ; that is, 13·6 times as high as mercury. But since mercury is 13·6 times as heavy as water, the weight of the column of water was exactly equal to that of the column of mercury in Torricelli's experiment, the tubes having the same section, and it was consequently the same cause, viz. the pressure of the atmosphere, which supported the two liquids. Pascal's other experiments with oil and with wine gave similar results. He found, for instance, that a column of oil stood at a height of about 37 feet.

128. **Amount of the atmospheric pressure.**—Let us assume that the tube in the above experiment is a cylinder the cross-section of which is equal to a square inch ; then, since the height of the mercurial column in round numbers is 30 inches, the column will contain 30 cubic inches, and as a cubic inch of mercury weighs $252{\cdot}5 \times 13{\cdot}6 = 3433{\cdot}5$ grains $= 0{\cdot}49$ of a pound (106), the pressure of such a column on a square inch of surface is equal to 14·7 lb. In round numbers, the pressure of the atmosphere is taken at 15 lb. on the square inch. A surface of a foot square contains 144 square inches, and therefore the force exerted upon it is equal to 2,160 lb. or nearly a ton.

A gas or a liquid which acts in such a manner that a square inch of surface is exposed to a pressure of 15 lb., is said to exert a pressure of *one atmosphere.* If, for instance, the elastic force of the steam of a boiler is so great that each square inch of the internal surface is exposed to a pressure of 90 lb. (= 6 × 15), we say it is under a pressure of six atmospheres. On the metric system the pressure of the atmosphere is equal to 1·033 kilogramme per square centimetre ; in practice an atmosphere is taken to be the pressure of a kilogramme on a square centimetre.

129. **Different kinds of barometers.**—The instruments used for measuring the atmospheric pressure are called *barometers.* In ordinary barometers the pressure is measured by the height of a column of mercury, as in Torricelli's experiment ; the barometers which we are about to describe are of this kind. But there are barometers without mercury, one of which, the aneroid (146), is remarkable for its simplicity and portability.

130. **Cistern barometer.**—Ordinary barometers are classed as *siphon* and *cistern* barometers. Fig. 122 represents the usual form of the cistern barometer. It consists of a glass tube, *ai*, closed at one end, about 33 inches long, and about ¼ inch in diameter. The tube is filled with mercury, and then its open end is inverted in mercury contained in a glass vessel, A, of a peculiar shape ; only the front half of this is visible, the other being fixed in a mahogany board which supports the whole barometer. The bottom of the cistern forms a spherical well, which is filled with mercury, and in which the tube *ai* is immersed. The tube is not fixed tightly in the neck, so that the atmospheric pressure is freely transmitted to the mercury of the bath, and thus supports the column of mercury *ai.* If the pressure increases, the mercury rises ; if it decreases, the mercury sinks.

Fig. 122.

At the top of the tube, on the right, is a scale divided in inches to measure the height of the mercury in the tube. The graduation starts from the zero, which is level with the mercury in the bath. Hence, if the top of the mercury at *a* stands at 30 inches, for instance, this signifies that the height of the column of mercury is

30 inches. Only a portion of the scale is given, since, under ordinary circumstances, the variations of the atmospheric pressure are within a very few inches. Where greater variations occur, as in the use of the barometer for measuring heights, the graduated part must be longer.

It will be observed that the starting point of the graduation, the zero, is at the level of the mercury in the cistern. But the zero of the scale does not always correspond to the level of the mercury in the cistern. For as the atmospheric pressure is not always the same, the height of the mercurial column varies; sometimes mercury is forced from the cistern into the tube, and sometimes from the tube into the cistern, so that, in the majority of cases, the graduation of the scale does not indicate the true height of the mercury To diminish this source of error, the cistern has the form represented in fig. 122. Its upper part, that corresponding to the level of the mercury, is about 4 inches in diameter; so that, whether the mercury passes from the cistern into the tube, or from the tube into the cistern, as it is spread over a large surface the variations in the level are very small and may be neglected.

To complete this description, it may be added, that on the scale is a small index, *c*, sliding along a vertical rod. When made level with the mercury this index points on the one side to the divisions on the graduated scale, and on the other side to certain designations, the meaning of which will be afterwards stated (137). In the middle of the tube are two thermometers, one with a Fahrenheit and the other with a Centigrade graduation.

131. **Fortin's barometer.**—*Fortin's barometer* (fig. 123) differs from that just described, in the shape of the cistern. The base of the cistern is made of leather, and can be raised or lowered by means of a screw; this has the advantage that a constant level can be obtained, and also that the instrument is made more portable. For, in travelling, it is only necessary to raise the leather until the mercury, which rises with it, quite fills the cistern and the tube; the barometer may then be inclined, and even inverted, without any fear that a bubble of air may enter, or that the shock of the mercury may crack the tube.

Fig. 123 shows the details of the construction of the cistern. It consists of a glass cylinder *b*, which allows the mercury to be seen; the bottom of the cylinder is cemented to a boxwood cylinder, *zz*, on which is firmly fixed at *ii* the chamois leather *mn*, which is the base of the cistern. At the bottom of the leather is a small

wooden button, *x*, against which the screw C works, by which it is raised or lowered. This screw works in the bottom of a brass cylinder, G, which is fastened on the glass cylinder. Fixed to the lid of the cistern is a small ivory pointer, *a*, the point of which exactly corresponds to the zero on the scale. The upper part of the cistern is closed by buckskin, *ce*, which is fastened to the barometer tube, E, and to a tubulure in the wooden lid M, which covers the cistern. The barometer tube is drawn out at the open end, which is immersed in the mercury. The atmospheric pressure is transmitted through the pores of the leather. When an observation is taken with this barometer the mercury is first made level with the point *a*, which is effected by turning the screw, C, either in one direction or the other. In this manner the distance of the top, B, of the column of mercury from the ivory point *a* gives exactly the height of the barometer, for the graduation is measured from the point *a*. Lastly, the lower part of the cistern is enclosed in a brass case, which is connected with a lid by three rods, *k*, *k*, *k*. To the cistern is screwed a long brass case, which encloses the whole of the tube, as seen in fig. 124. At the top of this case there are two longitudinal slits, on opposite sides, so that the level of the mercury, B, is seen. The scale on the case is graduated in millimetres or in inches. An index, A, moved by the hand, gives, by means of a vernier, the height of the mercury to $\frac{1}{20}$ of a millimetre. At the bottom of the case is affixed a thermometer to indicate the temperature.

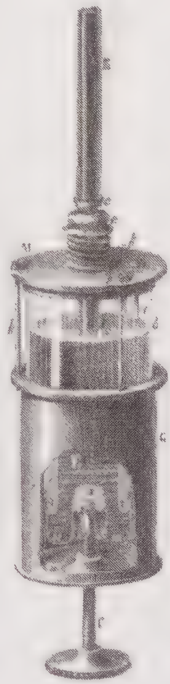


Fig. 123.

Fig. 124.

132. **Gay-Lussac's siphon barometer.**—The siphon barometer

has no cistern, but consists of a bent glass tube (fig. 125), one of the branches of which is much longer than the other. The longer branch, which is closed at the top, is filled with mercury as in the cistern barometer ; while the shorter branch, which is open, serves as a cistern. The difference between the two levels is the height of the barometer.

Fig. 125.

Fig. 126.

Fig. 127.

Fig. 128.

Fig. 125 represents the siphon barometer as modified by Gay-Lussac. In order to render it more available for travelling by preventing the entrance of air, he joined the two branches by a capillary tube ; when the instrument is inverted (fig. 126), the tube always remains full in virtue of its capillarity, and air cannot penetrate into the longer branch. A sudden shock, however, might separate the mercury and admit some air. To prevent this, Bunsen introduced an ingenious modification into the apparatus. The longer

branch, A, is drawn out to a fine point, and is joined to a tube, B, of the form represented in fig. 127. By this arrangement, if air passes through the capillary tube it cannot penetrate the drawn-out extremity of the longer branch, but lodges in the upper part of the enlargement B. In this position it does not affect the observation, since the vacuum is always at the upper part of the tube; it is, moreover, easily removed. Fortin's barometer (131) is generally also provided with an air-trap of this kind.

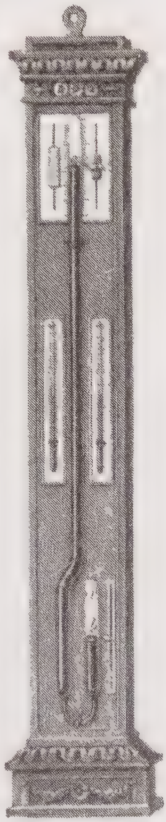


Fig. 129.

In Gay-Lussac's barometer the shorter branch is closed, but there is a very minute hole in the side *i* (fig. 127), through which the atmospheric pressure is transmitted.

The barometric height is determined by means of two scales (fig. 129), which have a common zero at the middle of the longer branch, and are graduated in contrary directions, the one from the middle to *a*, and the other from the middle to *b*, either on the tube itself or on brass rules fixed parallel to the tube. Two sliding indexes are moved until they correspond to the levels of the mercury in *a* and *b*. The total height of the barometer *a b* is the sum of the distances from the middle to *a* and *b* respectively.

Fig. 128 represents a very convenient mode of arranging the open end of a siphon barometer for transport. The quantity of mercury is so arranged that when the Torricellian space is quite filled with mercury, by inclining the tube the enlargement is just filled to *d*. This is closed by a carefully fitted cork, fixed on the end of a glass tube, *do*, about a millimetre in diameter, which allows for the expansion of mercury by heat. When the barometer is to be used, the cork and tube are raised.

133. **Precautions in reference to barometers.**—In constructing barometers, mercury is chosen in preference to any other liquid. For, being the densest of all liquids, it stands at the least height. When the mercurial barometer stands at 30 inches, the water-

barometer would stand at about 34 feet. It also deserves preference because it does not moisten glass. It is necessary that the mercury be pure and free from oxide; otherwise it adheres to the glass and tarnishes it. Moreover, if it is impure, its density is diminished, and the height of the barometer is too great. Mercury is purified, before being used for barometers, by treatment with dilute nitric acid, and by distillation.

The space at the top of the tube (figs. 121 and 129), which is called the *Torricellian vacuum*, must be quite free from air and from aqueous vapour, for either would depress the mercurial column. Now, glass tubes always condense aqueous vapour on their surface (73). Under the ordinary pressure of the atmosphere this layer of moisture adheres to the glass; but in a vacuum, where there is no pressure, it escapes, and there is formed a mixture of air and aqueous vapour which depresses the mercurial column.

The air and moisture can only be got rid of by boiling the mercury in the tube. To obtain this result a small quantity of pure mercury is placed in the tube and boiled for some time in a suitable apparatus. It is then allowed to cool, and a further quantity, previously warmed, added, which is boiled—and so on, until the tube is quite full; in this manner the moisture and the air which adhere to the sides of the tube pass off with the mercurial vapour.

A barometer is free from air and moisture if, when it is inclined, the mercury strikes with a sharp metallic sound against the top of the tube. If there is air or moisture in it, the sound is deadened.

Owing to the capillary depression produced in liquids which do not moisten glass, the height of the column of mercury is somewhat lower than the true height, and to a greater extent the narrower the tube. Accordingly a correction must be made for this, which with a tube 10 mm. in diameter amounts to 0·32 mm.; for a tube 20 mm. in diameter this correction is so small as to be negligible, and accordingly standard mercury barometers are made of at least this width.

In siphon barometers a correction is not necessary, since the capillary depressions in the two limbs act in opposite directions, and thus neutralise each other.

The Torricellian space at the top of the barometer tube is not an absolute vacuum, since it contains the vapour of mercury. The existence of this was demonstrated by an experiment of Dewar,

who applied a sponge filled with liquid air against a vessel in which the vacuum had been made ; the intense cold caused by the evaporation of the air produced a deposition of the mercury on the sides of the vessel, in the form of a brilliant metallic layer.

134. **Glycerine barometer.**—Jordan constructed a barometer in which the liquid used is pure glycerine. This has the specific gravity 1·26, and therefore the length of the column of liquid is rather more than ten times that of mercury ; hence small alterations in the atmospheric pressure produce considerable changes in the height of the liquid. The tube consists of ordinary composition gas tubing about ⅜ of an inch in diameter and 28 feet or so in length ; the lower end is open and dips in the cistern, which may be placed in a cellar ; the top is sealed to a closed glass tube an inch in diameter, in which the fluctuations of the column are observed. This may be arranged in an upper story, and the tubing, being easily bent, lends itself to any adjustment which the locality requires.

The vapour of glycerine has very low pressure at ordinary temperatures, and hence there is not so much objection to the use of glycerine for barometric purposes as there would be to that of water. On the other hand, it readily attracts moisture from the air, whereby the density, and therewith the height, of the liquid column vary. Hence it is usual to cover the liquid in the cistern with a layer of paraffin oil.

135. **Variations in the height of the barometer.**—When the barometer is observed for several days, its height is found to vary in the same place, not only from one day to another, but also during the same day. The extent of these variations—that is, the difference between the greatest and the least height—is different in different places. It increases from the equator towards the poles. The greatest variations are observed in winter.

The *mean daily height* is the height obtained by dividing the sum of twenty-four successive hourly observations by 24. In our latitudes, the barometric height at noon corresponds to the mean daily height.

The *mean monthly height* is obtained by adding together the mean daily height for a month, and dividing by 30.

The *mean yearly height* is similarly obtained.

Under the equator, the mean annual height at the level of the sea is 758 mm., or 29·84 inches. It increases from the equator, and between the latitudes 30° and 40° it attains a maximum of 763 mm.,

or 30·04 inches. In lower latitudes it decreases, and in Paris it does not exceed 759·8 mm., or 29·79 inches.

The general mean at the level of the sea is $0^{m}\cdot761$, or 29·96 inches. The mean monthly height is greater in winter than in summer, in consequence of the cooler atmosphere.

Two kinds of variation are observed in the barometer: 1st, the *accidental variations* or changes, which present no regularity; they depend on the seasons, the direction of the winds, and the geographical position, and are common in our climates; 2nd, the *daily variations*, which are produced periodically at certain hours of the day.

At the equator, and between the tropics, accidental variations are very infrequent; but the daily variations take place with such regularity that a barometer may serve to a certain extent as a clock. The barometer sinks from midday till towards four o'clock; it then rises, and reaches its maximum at about ten o'clock in the evening. It then again sinks, and reaches a second minimum towards four o'clock in the morning, and a second maximum at ten o'clock.

In the temperate zones there are also daily variations, but they are detected with difficulty, since they occur in conjunction with accidental variations. The hours of the maxima and minima appear to be the same in all climates, whatever be the latitude; they merely vary a little with the seasons.

136. **Causes of barometric changes.**—It is observed that the course of the barometer is generally in the opposite direction to that of the thermometer; that is, that when the temperature rises the barometer falls, and *vice versâ*; which indicates that the barometric changes at any given place are produced by the expansion or contraction of the air, and therefore by its change in density. If the temperature were the same throughout the whole extent of the atmosphere, no currents would be produced, and at the same height the atmospheric pressure would be everywhere the same. But when any portion of the atmosphere becomes warmer than the neighbouring parts, its specific gravity is diminished, and it rises and passes away through the upper regions of the atmosphere; whence it follows that the pressure is diminished, and the barometer falls. If any portion of the atmosphere retains its temperature, while the neighbouring parts become cooler, the same effect is produced; for in this case, too, the density of the first-mentioned portion is less than that of the others. Hence also it usually happens that an extraordinary fall of the barometer at

one place is counterbalanced by an extraordinary rise at another place. The daily variations appear to result from the expansions and contractions, which are periodically produced in the atmosphere by the heat of the sun during the rotation of the earth.

137. **Relation of barometric changes to the state of the weather.**— It has been observed that, in our climate, the barometer is generally above 30 inches in fine weather, and is below this point when there is rain, snow, wind, or storm, and also that, for any given number of days on which the barometer stands at 30 inches, there are as many fine days as rainy days. From this coincidence between the height of the barometer and the state of the weather, the following indications have been marked on the barometer, counting by thirds of an inch above and below 30 inches :—

Height	State of the weather
31 inches	Very dry
$30\frac{2}{3}$ "	Settled weather
$30\frac{1}{3}$ "	Fine weather
30 "	Variable
$29\frac{2}{3}$ "	Rain or wind
$29\frac{1}{3}$ "	Much rain
29 "	Storm

In using the barometer as an indicator of the state of the weather, we must not forget that it really only serves to measure the pressure of the atmosphere, and that it only rises and falls as this pressure increases or diminishes ; and although a change of weather frequently coincides with a change in the pressure, they are not necessarily connected. This coincidence arises from meteorological conditions peculiar to our climate, and does not always occur. That a fall in the barometer usually precedes rain in our latitudes is caused by the position of Europe. The most frequent winds are the south-west and north-east. The former coming to us from the equatorial regions are warmer and lighter. They often, therefore, blow for hours or even days in the higher regions of the atmosphere before manifesting themselves on the surface of the earth. The air is therefore lighter, and the pressure lower. Hence a fall of the barometer is a probable indication of the south-west winds, which gradually extend downwards, and, reaching us after having traversed large tracts of water, are charged with moisture, and bring us rain.

The north-east wind blows simultaneously above and below, but

the hindrances to the motion of the current on the earth, by hills, forests, and houses, cause the upper current to be somewhat in advance of the lower one, though not so much as the south-west wind. The air is, therefore, somewhat heavier even before we perceive the north-east, and a rise of the barometer affords a forecast of the occurrence of this wind, which, as it reaches us after having passed over the immense tracts of dry land in Central and Northern Europe, is mostly dry and fine.

The case is different in other countries. Thus on the eastern coast of South America, at the mouth of the River Plate, winds from the south-east bring rain and by their low temperature cause the barometer to fall.

When the barometer rises or sinks slowly—that is, for two or three days—towards fine weather or towards rain, it has been found, from a great number of observations, that the indications are then extremely trustworthy. Sudden changes in either direction indicate bad weather or wind.

Fig. 130.

138. **Wheel-barometer.**—Fig. 130 represents the principle of the *wheel-barometer*, which was invented by Hooke (in 1665); it is a siphon barometer, and in the shorter leg there is a float which rises and falls with the mercury. A string attached to this float passes round a pulley, and at the other end there is another and somewhat lighter weight. An index fixed to the pulley moves round a graduated circle, on which is marked *variable*, *rain*, *fine weather*, etc. When the pressure varies the float rises or sinks, and moves the index round to the corresponding points on the scale.

The barometers ordinarily met with in houses, and which are called *weather-glasses*, are of this kind. They are, however, of little use, for two reasons. The first is that they are neither very delicate nor precise in their indications. The second, which applies equally to all barometers, is, that those commonly in use in this country are made in London, and the indications, if they are of any value, are only so for a place at the same level and of the same climatic conditions as London. Thus a barometer standing at a certain height in London would indicate a certain state of weather, but

if removed to Shooter's Hill it would stand half an inch lower, and would indicate a different state of weather. As the pressure differs with the level and with geographical conditions, it is necessary to take these into account if exact data are wanted.

139. **Weight-barometer.**—Great attention has been paid of late years to the systematic observations of meteorological instruments, and fig. 131 represents the essential parts of a self-acting arrangement by which changes in the barometric height may be observed and recorded. It is an application of what is called a *weight-barometer*.

The barometer-tube is much wider at the top, *B*, and the other end, *A*, which dips in mercury, is drawn out to a fine point. The barometer is suspended by a stirrup, *C*, to one arm, *D*, of a scale-beam. The other arm, *F*, is bent downwards, and is provided with a sliding weight, by which the barometer may be counterpoised. To the beam is fixed a spring indicator, *K*, which has a pencil, *R*, at the end. This presses against a strip of paper, *P P*, which, by means of a clockwork arrangement, not represented in the figure, is moved at a regular and definite rate.

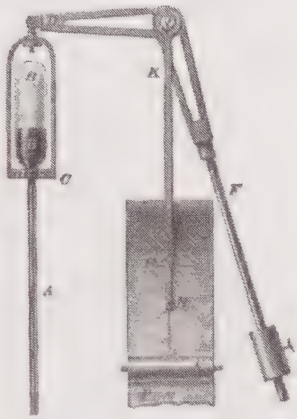


Fig. 131.

If now the barometer is stationary, and the clockwork is in motion, the pencil, *R*, will describe a straight line on the paper as it moves. If, however, the pressure of the atmosphere increases, the column of mercury becomes heavier, for it is longer, the scale-beam sinks somewhat on the side of *D*, and therewith the index, *R*, moves to the right. The reverse is the case when the pressure of the atmosphere decreases. Hence, as the pressure varies, the pencil will trace out a curve on the paper; and, by calculations based on the construction and dimensions of the apparatus, which are determined once for all for each instrument, the numerical significance of the curve is obtained at a glance.

140. **Determination of the heights of places by the barometer.**—One of the most important of the uses of the barometer has

been its application to the measurement of the heights of places above the sea level. For if we suppose the atmosphere divided into horizontal layers of equal thickness, a hundred, for instance, a barometer at the sea level would support the weight of a hundred of these layers. If it were raised in the atmosphere to the height of ten such layers, it would now only support the weight of ninety such layers ; and the mercury would therefore necessarily sink. It would sink still further if it were raised to the twentieth layer, and so on to the limit of the atmosphere, if that were possible. There it would be under no pressure, and the level of the mercury in the tube and in the cistern would be the same.

As the mercury sinks in proportion as we rise in the atmosphere, we might, from the amount by which it is lower, deduce the height above the sea level. If air had everywhere the same density up to the extreme limit of the atmosphere, the calculation would be very simple ; for as mercury is about 10,500 times as heavy as air, an inch of the barometer would correspond to a column of air of about 875 feet ; hence, in ascending a mountain, a diminution of an inch in the height of the barometer would correspond to an ascent of about 875 feet. But the density of the air decreases as we ascend, for the layers of air necessarily support a less weight ; hence, the measurement of the heights by the barometer is not so simple as we have supposed. Very complete tables have, however, been constructed, by which the difference in height between any two places may be readily ascertained, if we know the corresponding heights of the barometer. For small elevations we may assume that an ascent of 900 feet produces a depression of an inch in the height of the barometer. For measuring heights by the barometer the aneroid (146) is extremely convenient.

On the top of the Righi the density of the air is only about $\frac{11}{14}$ of its density at the sea level ; or, what amounts to the same thing, 11 cubic feet of air at the sea level weighs as much as 14 cubic feet taken from the top of the mountain.

If a barometer be taken from the cellar to the fourth or fifth story of a large house, it will be found to stand $\frac{1}{10}$ of an inch or so lower.

141. **Height of the atmosphere.**—In virtue of the expansive force of the air, it might be supposed that the particles would expand indefinitely into the planetary spaces. But, as the air expands, its expansive force decreases, and is further weakened by the low temperature of the upper regions of the atmosphere, so that at a certain height the expansive force is balanced by the action of

gravity. It is therefore concluded that the atmosphere is limited. We may get an idea of the relation between the dimensions of the earth and its atmosphere, by imagining a globe 1 foot in diameter covered by an envelope of paper about $\frac{1}{13}$ of an inch in thickness. In the lower regions of the air 13 cubic feet of air weigh one pound; at a height of 36 miles calculation shows that 84,000 cubic feet have that weight.

From the density of the atmosphere, and its decrease with increasing distance from the ground, the height of the atmosphere has been calculated at not less than 45 miles. Observations of shooting-stars make it probable that they become visible at a height of from 90 to 130 miles. As their luminosity is ascribed to the heat developed by their friction against the atmosphere (23) we must suppose that at this great height there is some atmosphere, though it must be extremely attenuated.

142. **The pressure of the atmosphere is transmitted in all directions.**—The atmosphere, like any other mass of fluid (84), must necessarily transmit its pressure in all directions, upwards and laterally as well as downwards. A striking instance of this is seen in the Magdeburg hemispheres (125), and the following experiment furnishes another illustration of this point.

A tumbler full of water is carefully covered with a sheet of paper which is kept in position by one hand, while with the other the tumbler is inverted. Removing then the hand which held the paper, the water does not fall out, both water and paper being kept in position by the upward pressure (fig. 132).

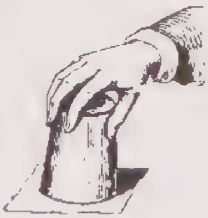


Fig. 132.

Fig. 133.

The object of the paper is to present a flat surface of water, for otherwise the water would divide, and would allow air to enter, and then the experiment would fail.

The use of the *wine-tester* also depends on the pressure of the atmosphere. It consists of a tin tube (fig. 133) terminating at the bottom in a small cone, the end of which, *o*, is open; at the top there is a small aperture, which is closed by the thumb. The two ends being open, the tube is immersed in the liquid to be tested;

closing then the upper end by the thumb, as shown in the figure, the tube is withdrawn, and remains filled in consequence of the pressure at *o*. But if the thumb be withdrawn, the pressure is transmitted both upwards and downwards, and the liquid flows out in obedience to the action of gravity. The *pipette* (fig. 134), which is used for adding a measured number of drops, is similarly explained.

Fig. 134.

143. **Pressure supported by the human body.**—The surface of the body of a man of middle size is about 16 square feet; the pressure, therefore, which a man supports on the surface of his body is about 34,000 lb. or 15 tons. Such an enormous pressure might seem impossible to be borne; but it must be remembered that in all directions there are equal and contrary pressures which counterbalance one another. It might also be supposed that the effects of this force, acting in all directions, would be to press the body together and crush it. But the solid parts of the skeleton could resist a far greater pressure; and as to the liquids contained in the organs and vessels, it is clear from what has been said about liquids (84) that they are virtually incompressible. The internal air, too, is compressed by the weight of the atmosphere, and is under the same pressure as the outer air, but resists it in virtue of its elasticity, being, in short, like a bottle full of air. The sides of the latter are pressed in by the weight of the atmosphere; but they can stand this, however thin their walls, for the pressure of the gas from within quite counterbalances that which presses on the outside.


Fig. 135.

The following experiment (fig. 135) illustrates the effect of atmospheric pressure on the human body. A glass vessel open at both ends, being placed on the plate of the air-pump, the upper end of the cylinder is closed by the hand and the pump is worked. The hand then becomes pressed by the weight of the atmosphere, and can only be taken away by a great effort. And as the elasticity of the gas contained in the

organs is not counterbalanced by the weight of the atmosphere the palm of the hand swells, and blood tends to escape from the pores.

In balloon ascents and on very high mountains, travellers experience a strong pressure of blood towards the nose and eyes, owing to the fact that the elastic force of the enclosed air preponderates over the greatly diminished pressure of the outer air.

A curious illustration of this influence of atmospheric pressure is met with in the structure of the arms and legs: the upper armbone, with its enlarged and rounded end, is jointed in a smooth and vacuous cavity of the shoulder-blade; the upper thigh-bone is jointed in a similar manner (fig. 136). In ordinary circumstances, the pressure of the outer air keeps these limbs in their place, so that muscular force is not required to raise them. But in high mountain ascents a remarkable feeling of fatigue is felt; for then, owing to the diminished external pressure, the muscles are called upon to help in supporting the arms and legs.

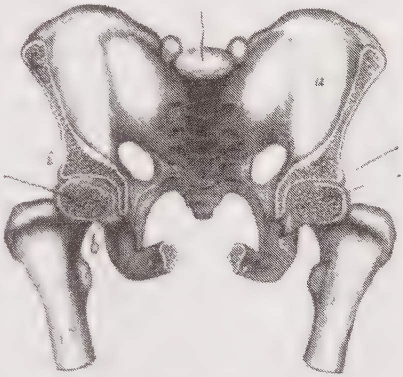


Fig. 136.

The operation of *cupping* in medicine is an application of the effect of removing the atmospheric pressure from the human body. The human mouth applied upon a cut, in the action of sucking, is a kind of cupping apparatus. The mouth of the leech is such an apparatus with one lancet.

Fig. 137.

Cupping is conveniently effected by means of the apparatus represented in fig. 137. The stout india rubber ball is compressed and the glass applied against the part treated. The sides of the ball resume their form, and in doing so produce a partial vacuum, so that if an incision in the skin has been made blood flows into the vessel.

CHAPTER II

MEASUREMENT OF THE ELASTIC FORCE OF GASES

144. **Boyle's law.**—The law of the compressibility of gases was discovered by Boyle in 1662 and subsequently in 1679, though independently, by Mariotte. It is in England called *Boyle's law*, and on the Continent *Mariotte's law*. It is as follows:—

'*The temperature remaining the same, the volume of a given quantity of gas is inversely as the pressure which it bears.*'

Fig. 138.

Fig. 139.

This law is easily verified by means of an apparatus called *Boyle's tube* (fig. 138). It consists of a long glass tube fixed to a vertical support; it is open at the top, and the other end, which is bent into a short vertical leg, is closed. On the shorter leg there is a scale which indicates equal *capacities*; the scale against the long leg

gives the heights. The zero in both scales is on the same horizontal line.

A small quantity of mercury is poured into the tube, so that its level in both branches is at zero, a condition which is effected without much difficulty. The air in the short leg is thus under the ordinary atmospheric pressure. If mercury be then poured into the longer tube, the volume of the air in the smaller tube is gradually reduced. If this be continued until the volume is only one-half—that is, until it is reduced from 10 to 5, as shown in fig. 139—and if the height of the mercurial column, CA, be measured, it will be found to be exactly equal to the height of the barometer at the time of the experiment. The pressure of the column CA is therefore equal to an atmosphere, which, with the atmospheric pressure acting on the surface of the column at A, makes two atmospheres. Accordingly, by doubling the pressure, the volume of the gas has been diminished to one-half.

Fig. 140.

Fig. 141.

If mercury be poured into the longer branch until the volume of the air is reduced to one-third its original volume, it will be found that the distance between the mercury surfaces of the two tubes is equal to two barometric columns. The pressure is now three atmospheres, while the volume is reduced to one-third.

The law also holds good in the case of pressures of less than one atmosphere. To demonstrate this, mercury is poured into a graduated tube, until it is about two-thirds full, the rest being air. It is then inverted in a deep trough, PM, containing mercury (fig. 140), and lowered until the levels of the mercury inside and outside the tube are the same, and the volume AB, which is then under a pressure of one atmosphere, is

noted. The tube is then raised as represented in fig. 141, until the volume of the air, AC, is doubled. The height of the mercury in the tube above the mercury in the trough CD is then found to be exactly half the height of the barometer at the time of the experiment. Accordingly, for half the pressure, the volume has been doubled.

Fig. 142.

In the experiment with Boyle's tube, since the quantity of air remains the same, its density must obviously increase as its volume diminishes, and *vice versâ*. The law may thus be enunciated: '*For the same temperature the density of a gas is proportional to its pressure.*' Hence, since water is 773 times as heavy as air, under a pressure of 773 atmospheres air would be, supposing the law to remain the same at that pressure, as heavy as water.

Boyle's law is not strictly true. For air and all gases except hydrogen the volume diminishes in a greater ratio than the pressure increases. For example, if the pressure is increased to 30 atmospheres the volume is reduced to something less than a 30th of its original value. The deviation from the law first increases and then diminishes; at a pressure of 152 atmospheres, about one ton per square inch, it vanishes, and air accurately obeys the law.

The deviations being small we may regard Boyle's law as being exact for all gases at ordinary pressures.

145. **Manometers.**—*Manometers* are instruments for measuring the pressure of gases or vapours. In all manometers the unit chosen is the pressure of one atmosphere, or 30 inches of mercury at the standard temperature, which, as we have seen (128), is 14·7 lb. to the square inch. The open-air *manometer* is represented in fig. 142 fixed against a board fastened to a wall and connected by a long tube C with a steam boiler, not shown in the figure. It consists of a glass tube about 20 feet in height, open at the top, and containing mercury in the enlargement A.

When the pressure of the steam in the boiler is equal to that of the atmosphere, the level of the mercury is the same in both branches,

At this level the number 1 is marked on the board. Then, since a column of mercury 30 inches in height represents a pressure of an atmosphere, the number 2 is marked at this height above 1; at a height of 30 inches above this the number 3 is marked, and so on, each interval of 30 inches representing an atmosphere. Thus, for instance, if the mercury has been forced up to $3\frac{1}{2}$, as represented in the figure, that would indicate that the pressure of the steam in the boiler is $3\frac{1}{2}$ atmospheres; so that, on each square inch of the inner surface of the boiler, there is a pressure of $3\frac{1}{2} \times 14{\cdot}7$ lb., or $51\frac{1}{2}$ lb.

Fig. 143.

The manometer with *compressed air* is founded on Boyle's law; it consists of a glass tube closed at the top (fig. 143), and filled with dry air. It is firmly cemented in a small bath containing mercury. By a tubulure, this bath is connected with the closed vessel containing either the gas or vapour whose pressure is to be measured.

In the graduation of this manometer, the quantity of air contained in the tube is such that, when the aperture communicates freely with the atmosphere, the level of the mercury is the same in the tube and in the bath. Consequently, at this level, the number 1 is marked on the scale to which the tube is affixed. As the pressure acting through the tubulure A increases, the mercury rises in the tube, until its weight added to the pressure of the compressed air is equal to the external pressure. It would consequently be incorrect to mark two atmospheres in the middle of the tube; for since the volume of the air is reduced to one-half, its elastic force is equal to two atmospheres, and, together with the weight of the mercury raised in the tube, is therefore more than two atmospheres. The position of the number is a little below the middle at such a height that the pressure of the compressed air, together with that due to the mercury in the tube, is equal to two atmospheres. The exact position of the numbers 2, 3, 4, etc., on the manometer scale can only be determined by calculation.

146. **Aneroid barometer.**—This instrument derives its name from the circumstance that no liquid is used in its construction

(ἀ, without, νηρός, moist). Fig. 144 represents one of the forms of these instruments ; it consists of a cylindrical metal box, partially exhausted of air, the top of which is made of thin corrugated metal, so elastic that it readily yields to alterations in the pressure of the atmosphere.

When the pressure increases, the top is pressed inwards ; when, on the contrary, it decreases, the elasticity of the lid, aided by a spring, tends to move it in the opposite direction. These motions are transmitted, by delicate multiplying levers, to an index which moves over a scale. The instrument is graduated by trial, its indications, under different pressures, being compared with those of an ordinary mercury barometer.

Fig. 144.

The aneroid has the advantage of being portable, and can be constructed of such delicacy as to indicate the difference in the pressure of the atmosphere between the height of an ordinary table and the ground. It is hence much used in surveying and in determining heights in mountain ascents. But it is somewhat liable to get out of adjustment, especially when it has been subjected to great variations of pressure ; and its indications should from time to time be compared with those of a standard barometer.

An aneroid indicating differences of one to two feet was used by the late Mr. Ralph Abercrombie, to determine the height of ocean waves, on a voyage from New Zealand to Cape Horn ; he found the average to be 47 feet.

MIXTURE AND SOLUTION OF GASES

147. **Mixture of gases.**—We have seen (98) that liquids, when they do not mix with or act chemically on each other, tend continually to separate, and to become superposed in the order of their densities. This is not the case with gases; being under a continual tendency to expand, when they mix, they do so in equal proportions in all parts of the vessel in which they are contained, and the pressure of the mixture is equal to the sum of the pressures of the constituents.

This result was shown experimentally by Berthollet, by means of an apparatus represented in fig. 145. It consisted of two glass globes provided with stopcocks, which could be screwed one on the other. The upper globe was filled with hydrogen, and the lower one with carbonic acid, which has 22 times the density of hydrogen. The globes having been fixed together were placed in the cellars of the Paris Observatory, and the stopcocks were then opened, the globe containing hydrogen being uppermost. Berthollet found, after some time, that the pressure had not changed, and that, in spite of the great difference in density, the two gases had become uniformly mixed in the two globes. Experiments made in the same manner with other gases gave the same results, and it was found that the diffusion was more rapid in proportion as the difference between the densities was greater.

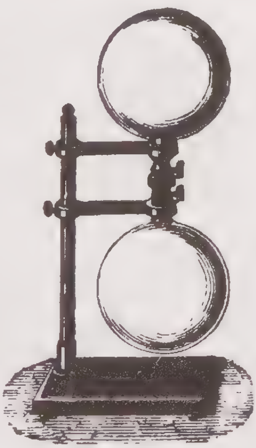


Fig. 145.

In accordance with this principle, air being a mixture of nitrogen and oxygen, which are different in density, its composition should be the same in all parts of the atmosphere, which, in fact, is what has been observed.

This is not inconsistent with the fact that there may be local accumulations of gases, such as carbonic acid in deep pits; in such cases some cause is at work producing the gas in question faster than it diffuses.

Mixtures of gases come under Boyle's law, like simple gases, as has been proved for air (144), which is a mixture of nitrogen and oxygen.

The diffusion of gases was investigated by Graham. Numerous experiments illustrate it, some of the most interesting of which are the following :—

A glass cylinder closed at one end is filled with carbonic acid gas, its open end tied over with a bladder, and the whole placed under a jar of hydrogen. Diffusion takes place between them through the porous diaphragm, and after the lapse of a certain time hydrogen has passed through the bladder into the cylindrical vessel in much greater quantity than the carbonic acid which has passed out, so that the bladder becomes very much distended outwards (fig. 146). If the cylinder be filled with hydrogen and the bell-jar

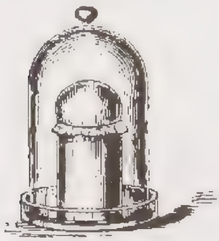


Fig. 146.

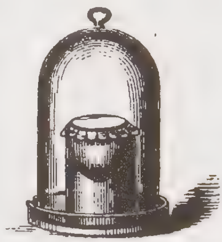


Fig. 147.

with carbonic acid, the reverse phenomenon will be produced—the bladder will be distended inwards (fig. 147).

A tube about 12 inches long, closed at one end by a plug of dry plaster of Paris, is filled with dry hydrogen, and its open end then immersed in a mercury bath. Diffusion of the hydrogen towards the air takes place so rapidly that a partial vacuum is produced, and mercury rises in the tube to a height of several inches (fig. 148). If several such tubes are filled with different gases, and allowed to diffuse into the air in a similar manner, in the same time, different quantities of the various gases will diffuse, and Graham found that the law regulating these diffusions is that *the quantity of a gas which passes through a porous diaphragm in a given time is inversely as the square root of the density of the gas.* Thus, if two vessels of equal capacity, containing oxygen and hydrogen, be separated by a porous plug, diffusion takes place; and after the

lapse of some time, for every one part of oxygen which has passed into the hydrogen, four parts of hydrogen have passed into the oxygen. Now, the density of hydrogen being 1, that of oxygen is 16; hence the diffusion is inversely as the square roots of these numbers. It is four times as great in the one which has $\frac{1}{16}$ the density of the other.

148. **Mixture of gases and liquids. Absorption of gases.**—Water and many other liquids possess the property of absorbing gases. Under the same conditions of pressure and temperature a liquid does not absorb equal quantities of different gases. At the ordinary temperature and pressure water dissolves $\frac{24}{1000}$ its volume of nitrogen, $\frac{48}{1000}$ its volume of oxygen, its own volume of carbonic acid, 3·5 times its volume of sulphuretted hydrogen, 43·5 of sulphurous acid, 450 of hydrochloric acid, and 729 times its volume of ammonia.

Fig. 148.

The number which expresses how many volumes of a gas one volume of a liquid will absorb is called its *coefficient of absorption*.

The general laws of gas-absorption are the following :—

I. *For the same gas, the same liquid, and the same temperature, the weight of gas absorbed is proportional to the pressure.* This may also be expressed by saying that at all pressures the volume dissolved is the same ; or that the density of the gas absorbed is in a constant relation with that of the external gas which is not absorbed.

Accordingly, when the pressure diminishes, the quantity of dissolved gas decreases. If a solution of a gas in water be placed under the air-pump and the pressure is diminished, the gas obeys its expansive force and escapes with effervescence.

The manufacture of aërated waters is a practical application of this law. By means of force-pumps (160) an excess of carbonic acid is dissolved in the water, and the solution is then preserved in carefully corked vessels. It is the carbonic acid dissolved in beer, in champagne, and in all effervescing liquids, which, rapidly escaping when the bottles are uncorked, produces the well-known report, and carries with it a greater or less quantity of the liquid.

II. *The quantity of gas absorbed is greater when the temperature*

is lower: that is to say, when the elastic force of the gas is less.

III. *The quantity of gas which a liquid can dissolve is independent of the nature and of the quantity of other gases which it may already hold in solution.*

For instance, if a given volume of water be already saturated with oxygen, of which it dissolves about $\frac{1}{30}$ of its volume, it would still dissolve its own volume of carbonic acid if it were placed in an atmosphere of that gas.

CHAPTER III

APPARATUS WHICH DEPEND ON THE PROPERTIES OF AIR

149. **Air-pump.**—The air-pump is an instrument by which a vacuum can be produced in a given space, or rather by which air can be greatly rarefied, for a perfect vacuum cannot be produced by its means. It was invented by Otto von Guericke in 1650, a few years after the invention of the barometer.

Fig. 149 gives a perspective view of the pump, fig. 150 gives a detailed longitudinal section, and fig. 151 a cross-section.

The pump consists of two stout glass barrels in which two pistons P and Q, made of leather well soaked with oil, move up and down, and close the barrels air-tight. The pistons are fixed to two racks, A and B, working with a pinion K (fig. 151), which is moved by the handle M N, so that when one piston rises the other descends.

The two barrels are firmly cemented on the base, H, which is of brass; on this plate is a column, I, terminated by a plate, G. On this plate is a glass bell-jar which is called the *receiver*. In the interior of the column is a conduit, which is prolonged below the base between the two barrels. It there branches in the shape of a T, terminating in two apertures, *a* and *b*, in the bottom of the cylinders. These apertures are conical, and are closed by two small conical valves; these latter are fixed to metal rods which work air-tight, but with gentle friction in the pistons. In the pistons is a cylindrical cavity communicating with the lower part of the pump by two apertures, *s* and *t* (fig. 151). These apertures are closed by small clack-valves, kept in position by springs which surround each of the rods themselves. The four valves, *a*, *b*, *s*, *t*, open upwards.

These details being known, the working of the machine is readily understood. It is sufficient to consider what takes place with respect to a single piston (fig. 150). As the piston, P, which is supposed to be at the bottom of its stroke, rises, it lifts the rod which traverses it, and therewith the valve *a*, which remains open

during the ascent. The valve, *t*, which is in the piston, remains closed by the action of the spring and by the pressure of the atmosphere, which acts in the barrel through an aperture, *r*, in the cover. From this position of the two valves, it will be seen that, as the piston rises, the external pressure of the atmosphere cannot act in the bottom of the barrel, but the air of the receiver, in virtue of its elasticity, expands and passes by the conduit, I and H, into the barrel. The receiver is still full of air, but it is more rarefied; it is less dense.

When the piston descends, the rod which bears the valve, *a*, descending with it, communication between the receiver and the

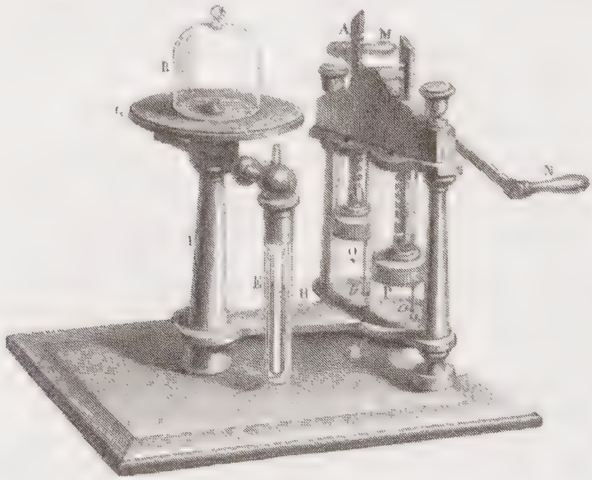


Fig. 149.

barrel is cut oft. The pressure of the air in the barrel increases, and finally overcomes the atmospheric pressure; so that the valve, *t*, being pressed upwards by the air in the interior more strongly than it is pressed downwards by the atmosphere, is raised, and allows the air of the barrel to escape into the upper part of the barrel, and thence into the atmosphere. Thus a certain quantity of air has been removed. A fresh quantity is removed at a second stroke of the piston, another at the third, and so on. The air in the receiver is thus gradually more and more rarefied; yet the air cannot be

entirely extracted, for it ultimately becomes so rarefied, both in the receiver and in the barrel, that when the piston, P, is at the bottom of its stroke, the compressed gas below the piston has no longer sufficient force to overcome the resistance of the atmosphere and raise the valve, *t*. The limit of rarefaction has then been attained, and it is useless to work the pump any longer.

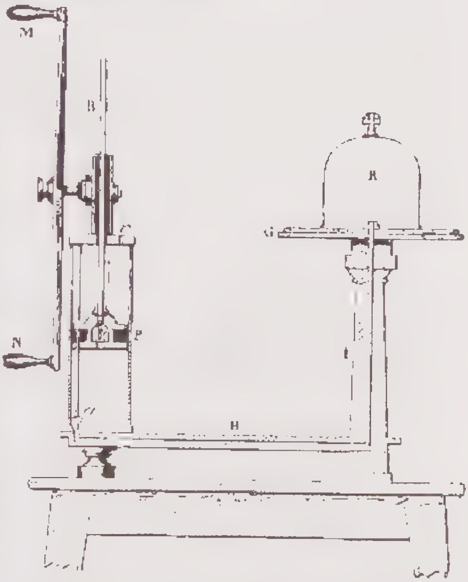


Fig. 150.

What has been said in reference to one barrel applies also to the other. The machine will work with one; and the first air-pumps had but one. The advantage of having two is that the vacuum is more rapidly produced and the labour much diminished. The use of double-action air-pumps was first introduced by Hawksbee.

150. **Measurement of the degree of rarefaction in the receiver.**—Since a perfect vacuum cannot be obtained in the receiver, it is useful to have a means of ascertaining the degree of rarefaction at any particular time. This is effected by means of a glass cylinder, E, connected by a brass tube with the conduit in the column I (fig. 149). In this cylinder is placed a bent glass tube, closed at one end and open at the other. This is called the *air-pump gauge*. It is fixed against a plate, on which is a graduated scale. The closed branch being at first full of mercury, so long as the air in the receiver, R, and in the cylinder, E, has sufficient pressure, it sustains the mercury in the tube, the height of which is from six to eight inches. But as the pump is worked, the air

becomes more and more rarefied, and the pressure is no longer sufficient to retain the column of mercury in the closed limb. It accordingly sinks in this limb and rises in the other. The greater the rarefaction, the smaller the difference of the level in the two limbs. They are, however, never exactly equal: that would correspond to a perfect vacuum. The mercury is usually at least $\frac{1}{20}$th of an inch higher in the closed branch. This is expressed by saying that a vacuum has been created within $\frac{1}{20}$th of an inch.

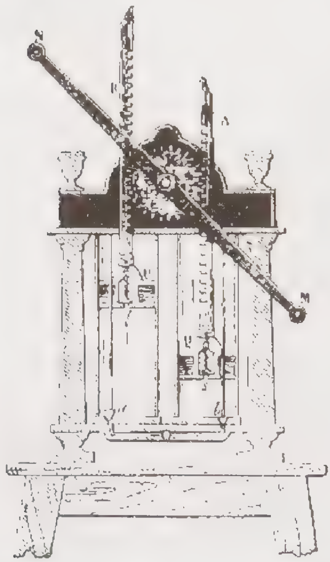


Fig. 151

Fig. 152.

151. **Uses of the air-pump.**—A great many experiments with the air-pump have been already described. Such are the mercurial rain (fig. 1), the fall of bodies in vacuo (fig. 45), the bladder (fig. 116), the bursting of a bladder (fig. 118), and the Magdeburg hemispheres (fig. 119).

The *fountain in vacuo* (fig. 152) is an experiment made with the air-pump, and shows well the elastic force of the air. It is an elongated flask, A, with a stopcock at the base, provided with a tube which projects in the interior and terminates in a fine nozzle.

The flask is screwed to the plate of the air-pump, the air inside it exhausted, the stopcock closed, and the apparatus placed in a vessel of water, R. When the stopcock is opened, the atmospheric pressure forces the water through the nozzle in a jet, as shown in the drawing.

By means of the air-pump it may be shown that air, by reason of the oxygen it contains, is necessary for the support of combustion and of life. For if we place a lighted taper under the receiver and begin to exhaust the air, the flame becomes weaker as rarefaction proceeds, and is finally extinguished. Similarly, an animal faints and dies if a vacuum is formed in a receiver under which it is placed. Fishes and reptiles support the loss of air for a still longer time than mammalia and birds.

152. **Application of the vacuum to the preservation of food.**—An important application has been made of the vacuum in preserving food. The germs present everywhere in air, under the influence of heat and moisture make animal and vegetable matters rapidly ferment and putrefy ; but if the air be properly removed from an enclosed vessel by exhausting, the contents may be kept fresh for many years.

Appert was the first, in 1809, to devise a means of preserving food in a vacuum, which consists in placing the substances to be preserved in tin vessels, which are closed hermetically, and then heated in boiling water for some time ; under the influence of heat the small quantity of oxygen left in the vessel is absorbed by the substance placed there, so that only nitrogen is present in the free state. Not only this, but the high temperature destroys the germs, which are the active agents in starting putrefaction.

Appert's method is now modified in the following manner. Instead of boiling the food while contained in the closed vessel, a small hole is left in the lid, through which escape the air and vapours produced during ebullition. When it is supposed that all the air has been expelled, a drop of melted lead is allowed to fall on the small hole in the cover which completely closes it. This method is practised on a large scale in preserving food and vegetables.

153. **Sprengel's air-pump.**—The air-pump described above does not enable us to reduce the air pressure in the receiver much below the $\frac{1}{20}$th of an inch. A more perfect vacuum can be obtained by means of Sprengel's mercury pump, one of the simplest forms of which is illustrated in fig. 153. The principle on which the pump

depends is that of converting the space to be exhausted into a Torricellian vacuum (133). A vertical glass tube—considerably longer than a barometer tube, and about 1mm. internal diameter—is connected by india rubber tubing with a reservoir of mercury, A. Mercury is allowed to fall in this tube at a rate regulated by a clamp at *c*; the lower end of the tube *c d* fits in the flask, B, which has a spout at the side a little higher than the lower end of *c d*; the upper part has a branch at *x*, to which the vessel to be exhausted is tightly fixed. When the clamp at *c* is opened, the first portions of mercury which run out close the tube and prevent air from entering below. As the mercury is allowed to run down the exhaustion begins, and the whole length of the tube from *x* to *d* is filled with cylinders of air and mercury moving downwards. Air and mercury escape through the spout of the flask, B, which is above the basin, H, where the mercury is collected. It is poured back from time to time into the funnel, A, to be re-passed through the tube until the exhaustion is complete. As this point is approached, the enclosed air between the mercury cylinders is seen to diminish, until the lower part of *c d* forms a continuous column of mercury about 30 inches high. Towards this stage of the process the falling mercury produces a noise like that of a water-hammer (55) when shaken; the operation is completed when the column of mercury encloses no air, and a drop of mercury falls on the top of

Fig. 153.

the column without enclosing the slightest air-bubble. The height of the column then represents the height of the column of mercury in the barometer; in other words, it is a barometer whose Torricellian vacuum is the receiver, R. This apparatus has been used with great success in experiments in which a very high exhaustion is required, as in the preparation of Geissler's tubes and of incandescent electric lamps. It may advantageously be combined with an exhausting syringe, which first removes the greater part of the air, the final exhaustion being completed as above.

154. **Condensing-pump.**—The condensing-pump is an apparatus for compressing air or any other gas. The form usually adopted is the following: in a cylinder, A, of small diameter (fig. 154), there is a solid piston the rod of which is worked by the hand. The cylinder is provided with a screw cock, C, which fits into the receiver, K. Fig. 155 shows the arrangement of the valves, which are so constructed that the lateral valve, *o*, opens inwards and the lower valve, *s*, downwards.

Fig.

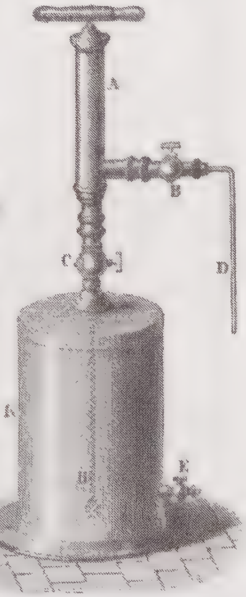


Fig. 154.

When the piston descends, the valve, *o*, closes, and the elastic force of the compressed air opens the valve, *s*, which thus allows the compressed air to pass into the receiver. When the piston ascends, *s* closes and *o* opens, and permits the entrance of fresh air, which in turn becomes compressed by the descent of the piston; and so on.

This apparatus is chiefly used for charging liquids with gases. For this purpose the stopcock, B, is connected with a reservoir of the gas, by means of the tube, D. The pump exhausts this gas, and forces it through the tube, H, into the vessel, K, in which the liquid is contained. When the liquid is sufficiently

saturated, the tap, C, is closed and the water can be drawn off by the stopcock, E. Artificial aërated waters are made by means of analogous apparatus; and one form of the condensing-pump is used for testing leakage and clearing away obstructions in gas-pipes.

Fig. 156.

On a larger scale the same principle is applied in compressing air in sinking cylinders for the purpose of building piers under water; and it is also applied in the atmospheric *railway-brakes*. An important application of condensed and rarefied air is met with in the *pneumatic post*, which is used in large towns for transmitting written telegraph despatches from local stations to a central station, where they are sent out by electricity. A bundle of such messages is placed in a *carrier*, which is an ebonite cylinder, about two inches in diameter, closed at one end and coated with flannel. This moves air-tight, but with very gentle friction, in a perfectly smooth metal tube which is laid underground and connects the stations. By means of suitable valves this tube can be placed in connection with large reservoirs of compressed or of rarefied air; and thus the carrier, with its contents, can be driven from one station by compressed air while it is drawn towards the other by the diminished pressure in front. The difference of pressure on the two faces is about two-thirds of an atmosphere, and this is sufficient to give a velocity of thirty miles an hour. In Paris the exact time is transmitted from a central clock by compressed air to public and private time-pieces in different parts of the city, with a slight retardation due in each case to the time required for transmission. These time-pieces or *pneumatic clocks* are not ordinary clocks, but their special mechanism is worked by the compressed air. Another application of compressed air is to the cleaning of carpets.

Torpedoes used in naval warfare are propelled by means of compressed air. The torpedo is a steel tube about 16 feet long with tapering ends. The gun-cotton to be exploded is contained in the front part or *head* of the torpedo, while compressed air occupies the after part, the engines worked by the compressed air being placed in the centre. When the torpedo is fired from a

suitable tube and strikes the water, its engines begin to work, and it is propelled at a distance below the surface which can be regulated beforehand, for a distance of half a mile at a high speed.

The excavators used in tunnelling are worked by compressed air.

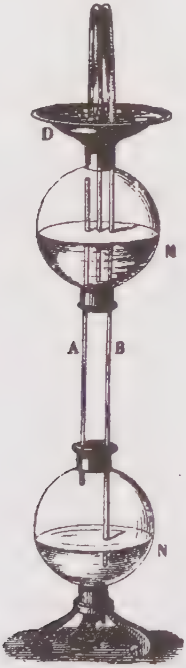


Fig. 157.


Fig. 158.

155. **Air-gun.**—This is an interesting application of the condensing-pump. At the end of the receiver is a valve which opens inwards and allows air to enter, but not to escape. To this receiver is screwed a barrel as represented in fig. 156, in which a piston works. When the piston is at the bottom of the barrel, air can escape through two side holes, *a*. When the piston is pushed down, air cannot escape from the reservoir ; the barrel

is filled with a fresh supply, which is pressed into the receiver, and so forth.

When the air in the receiver has been condensed, the charging-barrel is unscrewed and a firing-barrel screwed on. On touching a trigger (not represented in the figure) the valve is opened, a portion of air escapes, and projects the bullet ; the valve is closed again at once. Thus, when once the air-gun is charged, several shots may be fired in succession, though they become gradually weaker.

156. **Hiero's fountain.**—*Hiero's fountain* is an arrangement by which a jet may be obtained which lasts for some time. It derives its name from its inventor, Hiero, who lived at Alexandria, 120 B.C., and is an illustration of the elasticity of the air. It consists of a brass dish (fig. 157) and two glass globes. The dish communicates with the lower part of the globe by a long tube ; and another tube connects the two globes. A third tube passes through the dish to the lower part of the upper globe. This tube having been taken out, the upper globe is partially filled with water, the tube is then replaced, and water is poured into the dish. The water flows through the long tube into the lower globe and expels the air, which is forced into the upper globe ; the air thus compressed acts upon the water, and makes it jet out as represented in the figure. If it were not for the resistance of the atmosphere and friction, the liquid would rise to a height above the water in the dish equal to the difference of the level in the two globes.

157. **Intermittent fountain.**—The *intermittent fountain* consists of a stoppered glass globe, *a* (fig. 158), provided with two or three lateral tubes with fine nozzles. A glass tube, *d*, open at both ends, reaches at one end to the upper part of the globe, *a* ; the other end is fitted in a support, *c*, placed in the middle of the dish, *m*, which supports the whole apparatus. The support, *c*, is perforated with small holes, which allow air to pass into the tube just above a little aperture in the dish, *m*.

The water, with which the globe, *a*, is nearly two-thirds filled, runs out by the tubes, as shown in the figure ; the internal pressure being equal to the atmospheric pressure, together with the weight of the column of water, while the external pressure at that point is only that of the atmosphere. These conditions prevail so long as the lower end of the glass tube is open—that is, so long as air can enter and keep the air in *a* at the same pressure as the external air ; but the apparatus is arranged so that the orifice in the dish does not

allow so much water to flow out as is received from the upper tubes, in consequence of which the level gradually rises in the dish, and then closes the lower end of the glass tube. As the external air cannot now enter the globe *a*, the air becomes rarefied in proportion as the flow continues, unt its pressure, together with that due to the column of water from the level, *a*, to one of the nozzles, is equal to this external pressure ; the flow then stops. But as water continues to flow out of the dish at *m*, the tube opens again, air enters, and the flow recommences ; and so on as long as there is water in the globe *a*.

158. **Siphon inkstand.**—This vessel prevents ink from too rapid evaporation, and is an interesting illustration of the pressure of the atmosphere, and of the elasticity of air. It consists of a glass vessel of the shape of a truncated pyramid (fig. 159), closed everywhere except at the bottom, where there is a tubulure, which is always open. The inkstand is partially full of ink, while there is air at the top. The level of the ink inside being higher than in the tubulure, the pressure of the air inside is a little less than that of the atmosphere on the ink in the tubulure. As the ink there is used, its level sinks and is finally lower than the point *o*. At this moment a bubble of air passes into the interior, and, the pressure being thereby increased, the level of the ink descends in the inside and rises in the tubulure. This goes on until the internal level is at the point *o*. More ink must then be added, which is effected by pouring it into the tubulure, care being taken to incline the inkstand in the opposite direction. The fountains in birdcages are on a similar principle.

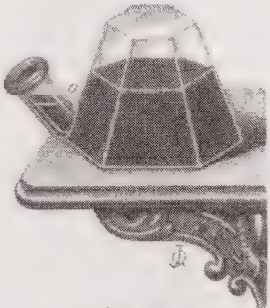


Fig. 159.

PUMPS

159. **Suction-pumps.**—Pumps are machines for raising liquids. Their invention, which is of great antiquity, is attributed to Ctesibius, a celebrated mechanician, who flourished at Alexandria 130 B.C. They are met with in many modifications, but may all be referred to three types—*the suction or lifting pump*, *the forcing-pump*, *and the suction and forcing pump*.

The suction or lifting pump, represented in fig. 160, consists of a cast-iron cylinder called the *barrel*, at the bottom of which is a pipe of a smaller diameter, which dips in the well. At the top of this pipe is a clack-valve, which is represented in the drawing as being closed. It moves easily up and down, and it establishes a communication between the cylinder and the body of the pump when it is open, and breaks it when closed. The piston in the barrel consists of a thick disc of metal or of leather, coated with tow or with leather. The piston is perforated by a small hole, which is closed by a valve; the valve is like that in the barrel, and, like it, opens upwards. The piston is worked by means of a long lever, which is the *handle*.

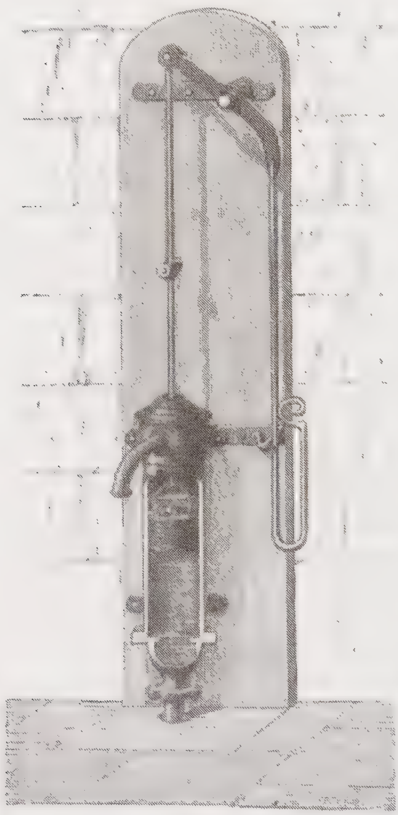


Fig. 160.

The manner in which the water is raised will be understood from an inspection of figs. 161, 162, and 163, which represent the piston and the valves in three different positions. When the pump has not been worked, the barrel and the pipe are full of air under the ordinary atmospheric pressure, which counterbalances the external atmospheric pressure on the well. Hence it follows that the level of the water inside and outside is the same. When the piston rises, since the valve c is pressed down by its own weight, and by that

of the atmosphere, the air is rarefied below it ; but, from its elastic force, the air which fills the pipe, B, soon opens the valve, *a*, and passes into the barrel. The air in the pipe, B, losing then in elastic force what it gains in volume (144), its pressure is no longer equal to the external pressure on the water in the well. Hence water rises in the pipe, as represented in the diagram. If now the piston sinks, the valve, *a*, closes ; and as the air thus enclosed in the barrel becomes more and more compressed, a moment arrives when its elastic force exceeds the pressure of the

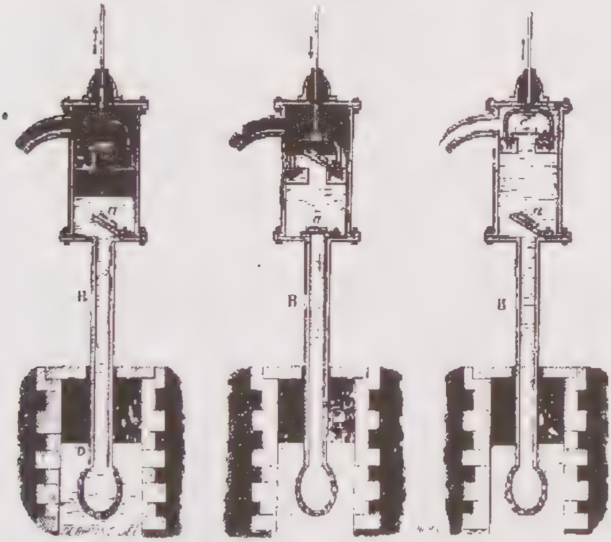


Fig. 161.　Fig. 162.　Fig. 163.

atmosphere ; the valve, *c*, is then raised, and air escapes into the top of the barrel, and thence into the atmosphere. With a second ascending stroke of the piston, the same phenomena are reproduced—that is, the valve, *c*, falls, and the valve, *a*, opens ; the water, being thus raised in the pipe, ultimately passes beyond the valve, *a* (fig. 161) and completely fills the barrel. From this time, when the piston re-descends, and the valve, *a*, closes, the pressure exerted on the water raises the valve, *c*, and the water passes above the piston (fig. 162). When once this effect is produced, the valve, *c*,

closes when the piston ascends, and the water which has passed above the piston, being raised with it, ultimately flows out by a spout in the side of the barrel.

Since it is the atmospheric pressure which raises the water in the pipe, the height of the valve, *a*, above the level in the vessel, cannot exceed a certain limit. A column of water, 34 feet in height, balances, as we have seen, the pressure of the atmosphere (133). Hence, if the pipe had a greater length than this, when once water had reached this height, the column of water in the pipe would balance the pressure of the atmosphere on the water of the well, and it could not be raised any higher. This, therefore, would be the extreme theoretical limit which the pipe could have; but in practice the height of the tube B does not exceed 20 to 26 feet: for, although the atmospheric pressure can support a higher column, the vacuum produced in the barrel is never perfect, owing to the

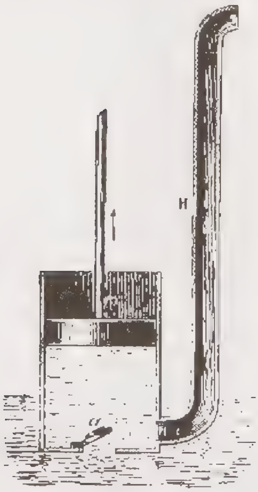


Fig. 164.

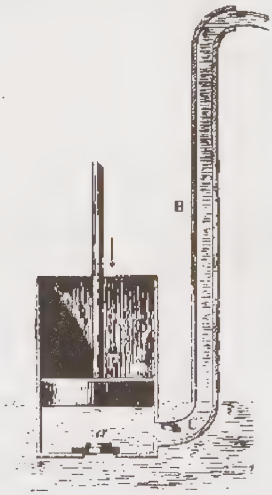


Fig. 165.

fact that the piston does not fit exactly on the bottom of the barrel. But when the water has passed the piston, it is the lifting force of the latter which raises it, and the height to which it can be brought depends on the force which works the piston.

160. **Force-pump.**—In this form of pump, water is not raised by the pressure of the atmosphere, but by the pressure of the piston on the water during its descent. For this purpose the piston is solid—that is, has no valve—and there is no lifting pipe, the barrel itself being immersed in the liquid to be raised (figs. 164 and 165). There are two valves in the barrel: one, *a*, in the bottom, opens upwards; the other, *c*, is placed in the orifice of a long tube in the side of the pump and opens away from the barrel.

When the piston rises (fig. 164), the air below it is rarefied, and atmospheric pressure closes the valve, *c*; while the water in which the pump is immersed, being forced by its own pressure and that of the atmosphere, raises the valve, *a*, and passes into the barrel, which it fills completely. The motion of the valve is just reversed when the piston descends (fig. 165). By its own weight and by the pressure upon it, the valve, *a*, closes, while the valve, *c*, opens and gives exit to the water in the barrel, which then rises to a height depending on the pressure exerted by the piston. If this amounts to a pressure of one atmosphere, water rises 34 feet in the pipe, H (133); if it is two atmospheres, water rises to 68 feet; and so on—that is, always to a height of 34 feet for a pressure of one atmosphere. The height, therefore, to which water can be raised in these pumps is not limited as it is in the suction-pump.

It will be seen, from what has been said, that water only rises in the pipe, H, when the piston descends; there is, therefore, an intermittent flow at the end of the pipe. A more regular flow is obtained by arranging two pumps, both forcing water into the same pipe, and in such a manner that when one piston rises the other sinks. It is by means of such an arrangement of two pumps that oil is raised to the wicks in Carcel's lamp. At the base of these lamps, and immersed in the oil itself, are two small pumps worked by a clockwork motion, which is wound up like a clock. Such a system is also applied in fire-engines.

161. **Fire-engine.**—In a *fire-engine* water has to be forced to a great height in a continuous stream. Fig. 166 represents a section of such a pump. Two rods, which work the pistons, *m* and *n*, in two brass barrels, are fixed by means of joints to the handle, PQ. Two pumps are placed in a trough, MN, of the same metal, called the *tank*, which is fed with water when the pump is at work. Between these two is an air-chamber, R, with a lateral aperture, Z, to which can be attached a long, flexible leather tube. This

tube is provided at the end with a long, conical copper tube, which has an aperture only about three-fifths of an inch in diameter.

The use of the air-chamber is as follows :—although the pistons work alternately, there would necessarily be some intermittence in the jet when they are at the top or at the bottom of their course. But the water, instead of being forced by the pumps directly into the rising pipe, first passes into the reservoir, as shown in fig. 166. Owing to the resistance in the tube and on the jet, it flows out of the reservoir more slowly than it enters. Its level rises in the

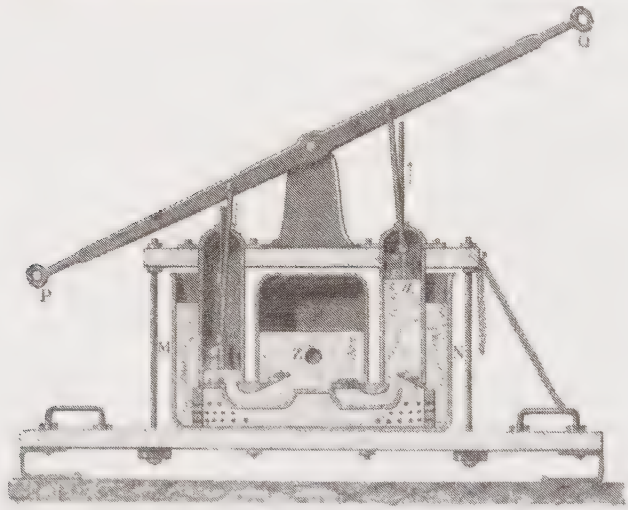


Fig. 166.

reservoir, and, as the air is thereby reduced in volume, its pressure increases, so that the compressed air, reacting on the water when the pistons stop, forces out the water and thus keeps up the continuity of the jet. A good fire-engine, worked by eight men, will raise water to a height of 100 feet.

162. **The siphon.**—The siphon is a bent tube open at both ends, and with legs generally of unequal length (fig. 167). It is used for transferring a liquid from one vessel to another without disturbing any sediment that may be present. It is worked in the following manner. Suppose the liquid to be water, and the siphon

to be filled with water and its ends closed. The shorter leg is then dipped in the liquid as represented in fig. 167; or, the shorter

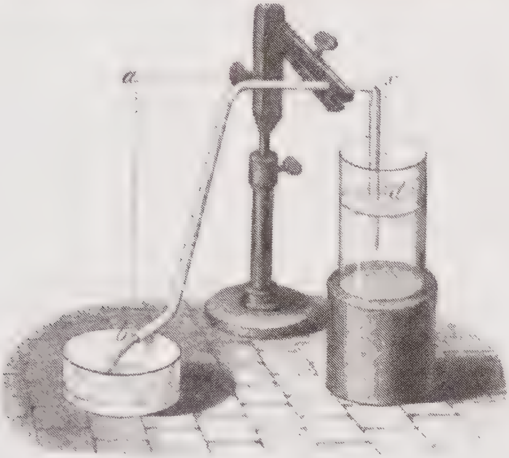


Fig. 167.

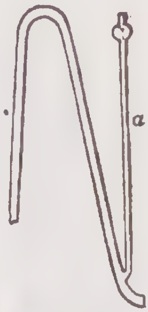


Fig. 168.

leg having been dipped in the liquid, the air is exhausted by applying the mouth at *b*. The air in the tube is thus rarefied, and the liquid in *d* rises and fills the tube in consequence of the

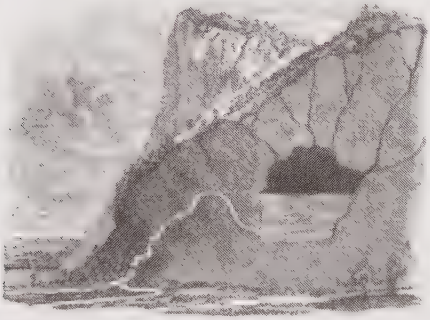


Fig. 169.

pressure of the air. It will then run out through the siphon as long as the level of the liquid is above the end of the longer leg.

A siphon of the form represented in fig. 168 is used where the presence of the liquid, such as sulphuric acid, for instance, in the mouth would be objectionable. A tube, *a*, is attached to the longer branch, and it is filled by closing the end of the longer limb, and sucking at the end of *a*.

To explain this flow of water from the siphon, let us suppose it filled and the short leg immersed in the liquid (fig. 167). Consider the water in the horizontal part of the siphon at the top. The pressure to which it is subjected is atmospheric pressure, less that due to the column of water, $c\,d$, that is, $H-h$, where $H =$ height of the water barometer, viz. 34 feet, and h, the height $c\,d$, also in feet. This pressure, if it acted alone, would drive the water in the direction $c\,a$. But if $a\,b=h'$, this same water is acted on by a pressure, $H-h'$, in the opposite direction. Thus, water will flow from c towards a only if $H-h$ is greater than $H-h'$, that is, if h' is greater than h: that is, b must be below the level of the water in the vessel.

163. **Intermittent springs. Tantalus' cup.**—In nature, springs are met with which stop spontaneously, and begin to flow again after a longer or shorter interval. This phenomenon depends on the action of the siphon, and is readily understood by reference to fig. 169, which represents a subterranean reservoir fed by water from a series of fissures in the earth; the channel by which the water flows out is on the left of the figure, and on coming to the surface the water forms a spring. In the figure the reservoir is represented as just being filled, and when the water rises to the height of the bend the siphon begins to act. If the fissures by which water is supplied furnish a smaller quantity than is carried away by the siphon-channel, the reservoir, together with the channel, is gradually emptied, and the flow then ceases. The reservoir gradually fills again, but the water cannot flow out until it has risen to the height represented by the dotted line, and the siphon has begun to work again. There is an excellent example of an intermittent spring at Giggleswick in Yorkshire.

Fig. 170.

The action of the toy known as *Tantalus' cup*, which is represented in fig. 170, illustrates that of intermittent springs; a curved siphon is arranged in a vessel, so that the shorter leg is near the

bottom of the vessel, while the longer leg passes through it. Being fed by a constant supply of water, the level gradually rises both in the vessel and in the tube to the top of the siphon, which it fills, and water begins to flow out. The apparatus is arranged so that the flow of the siphon is more rapid than that of the tube which supplies the vessel, and consequently the level sinks in the vessel until the shorter branch no longer dips in the liquid ; the siphon is then empty, and the flow ceases. But as the vessel is continually fed from the same source the level again rises, and the same series of phenomena is reproduced. The same principle is applied in automatic *flushing tanks* for sanitary purposes, and in an arrangement used by photographers for washing prints.

164. **Diving-bell.**—If the open end of a glass tumbler is placed on water so as to enclose the air, and if it is depressed, water enters until the pressure of the air inside is equal to the external pressure plus the pressure of the column of water from the level inside the tumbler to the level of the water outside.

The *diving-bell* is an application of this principle. The ordinary form is an elongated square iron box, open at the bottom, with seats along the sides for the workmen and their tools. In the top is a flexible pipe, through which fresh air is supplied by a compression pump, while that which is partially vitiated escapes in bubbles round the lower edges. Workmen can be lowered to considerable depths and remain there for some time.

CHAPTER IV

PRESSURE ON BODIES IN AIR. BALLOONS

165. **Archimedes' principle applied to gases.**—The pressure of a gas is exerted equally in all directions, as has been shown by the experiment with the Magdeburg hemispheres (125). It therefore follows that all which has been said about the equilibrium of bodies in liquids applies to bodies in air ; they lose a part of their weight equal to that of the air which they displace.

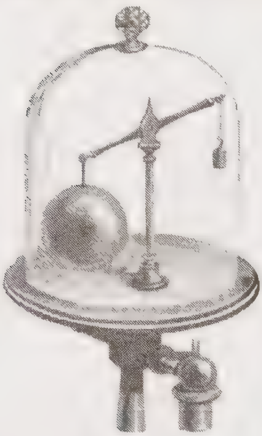


Fig. 171.

This loss of weight in air is demonstrated by means of the *baroscope*, which consists of a scale-beam, at one of whose ends a small leaden weight is supported, and at the other a hollow copper sphere (fig. 171). These are so constructed that in air they exactly balance one another, but when they are placed under the receiver of the air-pump, and a vacuum is produced, the sphere sinks, thereby showing that in reality it is heavier than the small leaden weight. Before the air is exhausted each body is buoyed up by the weight of the air which it displaces. But as the sphere is much the larger of the two, its weight undergoes most apparent diminution ; and thus, though in reality the heavier body, it is balanced by the small leaden weight. It may be proved, by means of the same apparatus, that this loss is equal to the weight of the displaced air, and we may thus generalise Archimedes' principle, and say that any body plunged in any fluid, whether it be a liquid or a gas, loses part of its weight equal to the weight of the displaced fluid. Hence the apparent weight of a body weighed in air is less than its real weight. To have an exact weight the volume of the weights and of the body weighed should

be exactly the same, which is seldom the case. The true weight of bodies is obtained by weighing them in a vacuum, or by making proper allowance for the air displaced.

The principle of Archimedes being thus true for bodies in air, all that has been said about bodies immersed in liquids applies to them—that is, that when a body is heavier than air it will sink, owing to the excess of its weight over the buoyancy of the air. If it is as heavy as air, its weight will exactly counterbalance the buoyancy, and the body will float in the atmosphere. If the body is lighter than air, the upward force due to the buoyancy of the air will prevail, and the body will rise in the atmosphere until it reaches a layer of the same density as its own. The force causing the ascent is equal to the excess of the buoyancy over the weight of the body. This is the reason why smoke, vapours, and air-balloons rise in the air.

166. **Air-balloons.**—*Air-balloons* are hollow spheres made of some light, impermeable material, which, when filled with heated air, with hydrogen gas, or with coal gas, rise in the air in virtue of their relative lightness.

They were invented by the brothers Montgolfier, of Annonay, and the first experiment was made at that place in June 1783. Their balloon was a sphere of 40 yards in circumference, and weighed 500 pounds. At the lower part there was an aperture, and a sort of boat was suspended, in which was burnt paper and straw. The heated air thus produced gradually inflated the balloon, and when it was full of expanded air, which was thus lighter than the external air, the weight of the balloon and its hot air being less than that of the air which it displaced, it soon rose to a height of more than 2,000 yards, to the great astonishment of the assembled spectators. It rapidly descended, however, for the hot air it contained soon became cooled in the higher regions of the atmosphere.

The experiment at Annonay excited great interest all over France, and, pending the repetition on a larger scale at the expense of the Government, Charles, a professor of physics, constructed a smaller balloon, about 13 feet in diameter, filled with hydrogen instead of heated air. The use of hydrogen is very advantageous, for, as it is 14 times as light as air, its ascensional force is far greater than that of hot air. Charles made an ascent in 1783 in a balloon inflated by hydrogen.

Since then the art of ballooning has been greatly extended, and many ascents have been made. That which Gay-Lussac made in

1804 was the most remarkable for the facts with which it has enriched science, and for the height which he attained—23,000 feet above the sea level. At this height the barometer stood at 12·6 inches, and the thermometer, which was 31° C. on the ground, was 9 degrees below zero.

In these high regions, the dryness was such, on the day of Gay-Lussac's ascent, that hygrometric substances, such as paper, parchment, etc., became dried and crumpled as if they had been placed near the fire. The respiration and circulation of the blood were accelerated in consequence of the great rarefaction of the air. Gay-Lussac's pulse made 120 pulsations in a minute, instead of 66, the normal number. At this great height the sky had a very dark blue tint, and an absolute silence prevailed.

One of the most remarkable ascents was made by Mr. Glaisher and Mr. Coxwell in a large balloon belonging to the latter. This was filled with 90,000 cubic feet of coal gas (sp. gr. 0·37 to 0·33, referred to air); the weight of the load was 600 pounds. The ascent took place at 1 P.M. on September 5, 1861; at twenty-eight minutes past 1 they had reached a height of 15,750 feet, and in eleven minutes afterwards a height of 21,000 feet, the temperature being $-10{\cdot}4°$; at ten minutes to 2 they were at 26,200 feet, with the thermometer at $-15{\cdot}2°$. At eight minutes to 2 the height attained was 29,000 feet, and the temperature $-19{\cdot}0°$ C. At this height the rarefaction of the air was so great and the cold so intense that Mr. Glaisher fainted, and could no longer observe. According to an approximate estimate, the lowest barometric height they attained was 7 inches, which would correspond to a height of 36,000 to 37,000 feet.

167. **Construction and management of balloons.**—A balloon (fig. 172) is made of long bands of silk sewn together and covered with india rubber varnish, which renders it air-tight. At the top there is a safety-valve closed by a spring, which the aëronaut can open at pleasure by means of a cord. A light wicker-work boat is suspended by means of cords to a network which entirely covers the balloon.

A balloon of the ordinary dimensions, which can carry three persons, is about 16 yards high, 12 yards in diameter, and its volume when it is quite full is about 680 cubic yards. The balloon itself weighs 200 pounds; the accessories, such as rope and boat, 100 pounds.

The balloon is filled either with hydrogen or with coal gas.

Although the latter is heavier than the former, it is generally preferred, because it is cheaper and more easily obtained. It is passed into the balloon from the gas-reservoir by means of a flexible pipe. It is important not to fill the balloon quite full, for the atmospheric pressure diminishes as it rises, and the gas inside, expanding in consequence of its elastic force, would tend to burst it. It is sufficient for the ascent if the weight of the displaced air exceeds that of the balloon by 8 or 10 pounds. The buoyancy due to this excess of weight is constant so long as the balloon is not quite distended by the expansion of the air in the interior. If the atmospheric pressure, for example, has diminished to one-half, the gas in the balloon, according to Boyle's law, has doubled its volume. The volume of the air displaced is therefore twice as great; but since its density has become only one-half, the weight, and consequently the upward buoyancy, is the same. When once the balloon is completely dilated, if it continue to rise, the force of the ascent decreases, for the volume of the displaced air remains the same, but its density diminishes, and a time arrives at which the buoyancy is only equal to the weight of the balloon. The balloon can now only take a horizontal direction, carried by the currents of air which prevail in the atmosphere. The aëronaut knows by the barometer whether he is ascending or descending; and by the same means he determines the height which he has reached. A

Fig. 172.

flag fixed to the boat would indicate by the position it takes, either above or below, whether the balloon is descending or ascending.

When the aëronaut wishes to descend, he opens the valve at the top of the balloon by means of the cord, which allows gas to escape, and the balloon sinks. If he wants to descend more slowly, or to rise again, he empties out bags of sand, of which there is an ample supply in the car. The descent is facilitated by means of a grappling iron fixed to the boat. When once this is fixed to any obstacle the balloon is lowered by pulling the cord.

Fig. 173.

The only practical applications which air-balloons have hitherto had have been in military reconnoitring. At the battle of Fleurus, in 1794, a *captive balloon*—that is, one fastened to the ground by a rope—was first used, in which there was an observer, who reported the movements of the enemy by means of signals. Captive balloons have been employed in most of the wars of the last fifty years, and at the present time most countries have a balloon department connected with their army system. During the siege of Paris (1870–1) many balloons were sent out by the beleaguered city, the majority of which, carrying passengers and despatches, successfully landed in parts of France unoccupied by the enemy. Many ascents were made by Mr. Glaisher for the purpose of making meteorological observations in the higher regions of the atmosphere (166). In recent years numerous attempts have been made to construct dirigible balloons, and some of these have met with a certain amount of success. In 1902 M. Santos-Dumont constructed

an air-ship in which, starting from the Parc d'Orient in Paris, he rounded the Eiffel Tower and returned to the spot from which he started. The air-ship consisted of an *aërostat* or balloon of cigar shape inflated with hydrogen and containing an air bag for compensation. Below this was suspended a very light frame-work to which was attached the motor, the propeller, the rudder, and a wicker basket chair for the aëronaut. The motor was a petrol engine of 16 horse-power, the parts of which were made as light as possible. The total weight of the apparatus was 550 lbs. From his seat M. Santos-Dumont was able to control the air bag (for keeping the axis of the cigar-shaped balloon horizontal), the rudder and the engine.

Flying machines must be distinguished from balloons in that in them little or no use is made of the buoyancy of the air, the elevation and motion being maintained by dynamic means. The lifting power of a kite and the pull exerted on the cord probably originated the idea of a plane surface suitably inclined so as to rise when a forward movement is imparted to it and maintained during the flight. A suitably designed *aëroplane* will rise in the air and carry its load when actuated by sufficient engine power, and many such aëroplanes have been designed in recent years; but no extended flights have been hitherto accomplished. Sir Hiram Maxim has designed several forms of aëroplane machines, the motive power being supplied by some kind of gas-engine (petrol or acetylene). Some details respecting one of these may be here given. The aëroplane was constructed of steel tubes pivoted to the main frame, so that its inclination to the latter could be altered, and was covered with fabric. Two propellers with spokes covered with silk were mounted on the frame below the aëroplane, and by driving these propellers at different speeds the machine could be steered to the right or left. The weight of the whole machine was 8,000 lbs., and the engine was of 363 horse-power, the screw thrust being more than 2,000 lbs. The total width was 200 feet. The machine was started on rails, and when the velocity reached 36 miles an hour, the whole machine was completely lifted from the rails. The experiments showed that a flying machine carrying its own engine, fuel, and passengers can be made powerful and light enough to lift itself in the air; also that an aëroplane will lift more than a balloon of the same weight. Success in aërial navigation in the future is to be looked for rather from the aëroplane than from the balloon.

168. **Parachute.**—The object of the parachute is to allow an

aëronaut to leave the balloon, by giving him the means of lessening the rapidity of his descent. It consists of a large, circular piece of cloth (fig. 173) about 16 feet in diameter, which by the resistance of the air spreads out like a gigantic umbrella. In the centre there is an aperture, through which the air, compressed by the rapidity of the descent, makes its escape; for otherwise oscillations might be produced, which, when communicated to the boat, would be dangerous.

In fig. 172 there is a parachute attached to the network of the balloon by means of a cord, which passes round a pulley, and is fixed at the other end to the boat. When the cord is cut, the parachute sinks, at first very rapidly, but more slowly as it becomes distended, as represented in fig. 173.

169. **Bellows.**—Fig. 174 represents a simple form of bellows, the action of which depends on the compression of air. Between two round wooden boards provided with handles, one of which has a valve, *k*, while the other works on a hinge, a folded leather bag

Fig. 174.

is fastened. The inner space terminates in front in a short iron or brass pipe, *d*, which is called the *nozzle*. If the upper lid is raised, the valve is opened, and air enters until the space is quite filled. When the handle is depressed the valve closes, the air is compressed, and forced out through the nozzle. Thus this arrangement, like that of the force-pump, produces an intermittent flow of air.

In the act of *breathing* the ribs are sunk, and the diaphragm is thereby raised; by this means the chest is contracted, and the air in the lungs condensed, so that it is driven into the outer air. In drawing in air the diaphragm is depressed, and thereby the chest expanded; the air in the lungs is rarefied, and outer air enters to equalise the pressure.

When a current of air is forcibly drawn through a tube it exerts an aspirating action on the air in its immediate neighbourhood, as is well illustrated by the *spray-producer* (fig. 175). If we blow strongly through the tube, B, across the drawn-out top, *m*, of the tube, A, the liquid in A not only rises to the top, but is resolved into an infini-

tude of minute drops which are carried away with the current of air. This principle is applied on a large scale, using a current of steam instead of air, in *Giffard's injector* for supplying water to locomotives even while the train is running. Fig. 176 represents an apparatus easily constructed from glass tubes which illustrates its action, it being observed that the tubes, *d f a* and *h k*, are much longer horizontally and vertically than is here shown.

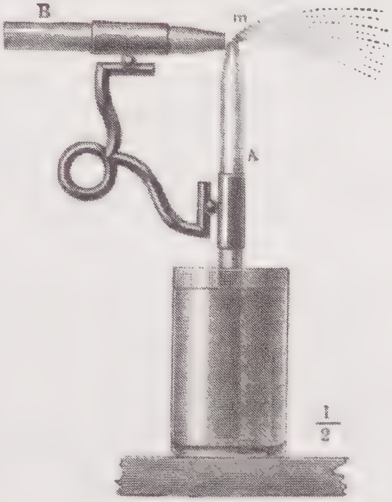


Fig. 175.

If the vertical tube, *f a*, is fitted into a vessel of boiling water as soon as steam issues through *o*, it not only raises water from a reservoir in which the bottom of the tube, *g h*, dips, but drives it through the aperture *o*. And if a bent tube, with a narrow opening like *o*, be fitted at *n*, and directed upwards, a continuous jet of water is produced, often reaching to the ceiling.

This apparatus serves well to illustrate the principle of *Giffard's injector*, an extremely ingenious and important apparatus by which steam boilers are kept supplied with water.

Fig. 176.

The principle is also applied in a series of machines for moving and lifting liquids, and even solids such as corn ; in pumping, in blowers, exhaust-pumps, etc.

BOOK IV

ON SOUND

CHAPTER I

PRODUCTION, PROPAGATION, AND REFLECTION OF SOUND

170. **Acoustics.**—This term is given to the scientific study of sounds, and of the vibrations of elastic bodies.

Music considers sounds with reference to the pleasurable feelings which they are calculated to excite in us. *Acoustics*, or the scientific study of sound, is concerned with the questions of the production, transmission, and comparison of sounds; to which may be added the physiological question of the perception of sounds.

Sound is a peculiar sensation excited in the organ of hearing by the vibratory motion of bodies, when this motion is transmitted to the ear through an elastic medium.

Take, for instance, the string of a musical instrument, when it is pulled or sounded by a bow (fig. 177). When it is pulled aside

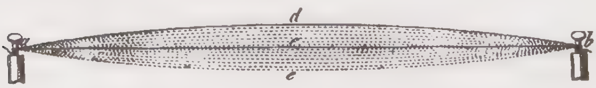


Fig. 177.

from the position *a c b*, where it is at rest, to the position *a d b*, all the points being more or less out of their position of equilibrium, and then left to itself, the string tends to revert to its original position, *a c b*, owing to its elasticity. From its acquired velocity, however, it passes beyond it as far as *a e b*, all the points being then virtually as far out of their position of rest as they were at *a d b*. But as

the elasticity still continues to act, not merely does the string revert to its original position, but it again passes beyond it ; and so on, the ***amplitude*** (60) of its oscillation becoming smaller and smaller, as represented by the dotted lines in the figure, until it ultimately comes back to its original state of equilibrium. Hence each point of the string makes a backward and forward, or *vibratory* motion, like that of the pendulum. The passage from the position *a d b* to *a e b*, and back to *a d b*, is called a *complete vibration* or *oscillation* ; the passage from *a d b* to *a e b*, or from *a e b* to *a d b*, is a *semi-vibration* or *semi-oscillation* (60).

Any body which vibrates in such a manner as to yield a sound is called a *sonorous* or *sounding* body. The vibrations of sounding bodies are generally too rapid to be directly counted, or even distinctly seen ; yet they may be rendered evident in a variety of ways. Thus, if a tolerably large bell jar, *a* (fig. 178), be made to sound by striking it with the finger, and a small ivory ball, suspended by a thread, be approached to it, the ball will be observed to receive a series of rapid shocks from the sides of the bell, showing that it is in a state of vibration. Or let a plate of metal be clamped horizontally (200) and sand be strewn over it ; when the plate is made to vibrate by briskly moving a violin bow against the edge, the sand becomes violently agitated, which is obviously due to the vibrations of the plate. A sound of very short duration is called a *report*.

Fig. 178.

171. **Propagation of sound in the air. Sound-waves.**—After having ascertained that when a body emits a sound, its molecules are in a state of vibration, it remains to explain how these vibrations are transmitted to the ear to produce the sensation of sound. Sound always requires for its transmission an elastic medium which at one end is in contact with the sounding body, and at the other with the organ of hearing. Air is the ordinary medium through which sound is transmitted. As air is very mobile, compressible, and elastic, its molecules, being in contact with different parts of the sounding body, acquire movements which are similar to those

of these parts; they go and come with these parts, so that each molecule of air in contact with the body is pushed forward by it, and returns, having communicated its motion to the next molecule; this then acts in the same manner on the next molecule, and so on to the molecules in contact with the *tympanum* or *drum* of the ear (210).

At each impulse imparted by a sounding body to the molecules of air in contact with it, these molecules pressing in turn upon the succeeding ones, a condensed part is produced in the air to a certain distance, which is called the *condensed wave*; then, when the vibrating body reverts to its original position, the molecules nearest to it follow in its motion, so that there is formed in the air a rarefied part, which follows the condensed wave, and which is called the *rarefied wave.* A condensed and a rarefied wave together form a *sound-wave.* A sounding body is a centre from which these waves are emitted all round it in the form of continually increasing spheres.

We may form some idea of the way in which sound is propagated in air by considering the analogous case of wave motion when a stone, for example, is thrown on a sheet of still water; it makes a depression in the water in the place where it falls, but immediately the water rises round the place in question, forming a raised circular ring which widens out gradually, losing in height as it gains in extent. This represents what we have spoken of above as a condensed wave. While this wave travels thus on the surface of the still water, the liquid rises at the centre of disturbance, and forms, instead of the original depression, an elevation of the same volume; this can only be done by producing around it a trough or valley, forming another ring, which is the counterpart of the raised one, being hollow instead of in relief. It closely follows the raised one in ever-widening circles, and the system, consisting of elevation and depression, forms a single complete wave. The *wave-length* is the distance from the top or *crest* of one wave to the crest of the next, or, what is the same thing, the distance between the lowest points of two successive hollows.

This description applies to the case of a single disturbance at the centre: a single condensed wave being formed followed by a single expanded one, the centre will have become again level, while the motion will continue at the circumference, progressing continually outwards, but becoming weaker and weaker. But if

the original disturbance has been sufficiently strong, which is ordinarily the case, the water at the centre will not come to rest at once, but will make a series of isochronous oscillations. Each of these oscillations produces a series of condensed and expanded waves chasing each other on the surface of the water.

Fig. 179 is an attempt to represent, by shading alternately dark and light, the succession of condensed and expanded waves, and their diminished amplitude as they get further and further away.

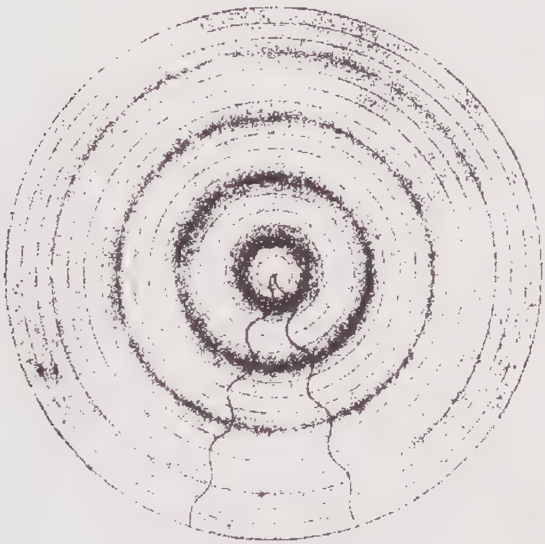


Fig. 179

In fig. 180 the elliptical dotted lines *a b c d* represent, in perspective, the series of waves, and the sinuous line, M N, represents a section of the waves by a vertical plane passing through the centre of disturbance ; the highest part of the wave above the horizontal line is the *crest*, and the lowest below, the *hollow*.

In the experiment described above, in which waves travel on the surface of water from a point of disturbance, it is important to notice that that which travels is the wave-form, and not the water of which the waves are composed. The water particles have

an up-and-down motion, while the form of the wave travels horizontally.

This is proved by the fact that floating particles such as bits of wood or cork bob up and down as the waves pass, being now on the crest, now in the hollow of a wave, but not travelling onwards with it. The vibrations in this case are said to be *transverse.*

In a wave of sound in air the air particles are, in one half of it, closer together, and in the other half less close together, than in still air through which no sound-wave is passing. These two parts together constitute the sound-wave. Each air particle moves to and fro like a little pendulum, *along* the line in which the sound is travelling, and such oscillations are said to be *longitudinal.* Thus, although disturbances are transmitted both on the surface of water and through air by wave motion, there is a fundamental difference between the two cases. In the former the water particles, by their *transverse* vibrations, give rise to a wave consisting of crest and

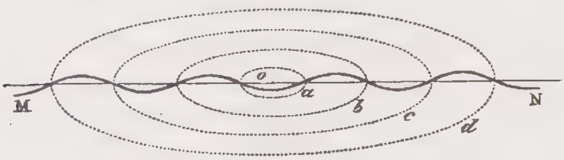


Fig. 180

hollow; while in the latter the air particles, by their *longitudinal* vibrations, set up waves, each of which is composed of a condensation and a rarefaction.

The report of a cannon travels through many miles, while the smoke which accompanies the sound is not driven far from the mouth of the piece. This is evidence that the transmission of sound is not due to the particles of air being themselves transported with the sound; again we shall see that sound is transmitted by solids, where there could be no possibility of any translatory motion of the particles.

This mode of transmission may be illustrated by suspending a number of glass balls, or, still better, billiard balls, by threads so that they are in close contact with each other (fig. 181). When the end one is raised, and allowed to strike against the next, the one at the other end flies off. Here the first ball imparts its momentum (69) to the second, then to the third, and so forth, the

effect being that, though apparently at rest, the motion is transmitted by the balls being alternately contracted and expanded.

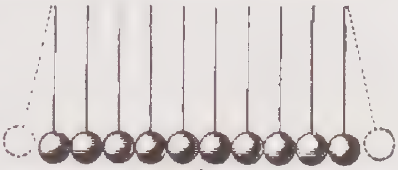


Fig. 181.

In the case of very loud sounds, the disturbance communicated to the air in the form of sound-waves may be very considerable. Thus the waves produced by thunder, by the report of cannon, and by the explosion of masses of gunpowder, are frequently powerful enough to break panes of glass and window-frames, and even to blow down buildings.

172. **Coexistence of sound-waves.**—It is to be observed that several sounds may be propagated in air without destroying each other. Thus in the most complicated orchestral music, a person with a practised ear can readily follow the sound of each instrument. Yet a loud sound interferes with a weak one; thus the sound of a drum overpowers that of the human voice. Sounds also which are too weak to be distinctly heard, accumulate upon each other, and produce a confused sound, which becomes perceptible to the ear. Such is the cause of the murmuring of water, the rustling of leaves in woods, and the dashing of waves against the sea shore.

173. **Sound is not propagated in a vacuum.**—The vibrations of elastic bodies can only produce the sensation of sound in us by the intervention of a medium interposed between the ear and the sounding body, and set in vibration by it. This medium is usually the air, but all gases, vapours, liquids, and solids also transmit sound.

Fig. 182.

The following experiment shows that the presence of a ponderable medium is necessary for the propagation of sound. A tolerably large glass globe (fig. 182), provided with a stopcock, has a small bell suspended in the interior by a thread. A vacuum having been created in the globe by means of the air-pump, no sound is emitted when the globe is shaken, though the clapper may be seen to strike against the bell; but if air or any other gas or vapour be admitted, sound is distinctly heard each time the globe is agitated.

The experiment may also be made by placing either a small metallic bell, which is continually struck by a small hammer by means of clockwork, or an ordinary musical-box, under the receiver of the air-pump. As long as the receiver is full of air at the ordinary pressure the sound is transmitted ; but, in proportion as the air is exhausted, the sound becomes feebler, and is imperceptible in a vacuum. To ensure the success of the experiment, the bell-work or musical-box must be placed on wadding or cotton-wool ; for otherwise the vibrations would be transmitted to the air through the plate of the machine.

Hence the loudest sounds on the earth could not be heard beyond the limits of the atmosphere ; and, conversely, not the slightest sound could reach our earth from the celestial bodies ; the most violent explosions could take place on the moon without our hearing them.

174. **Propagation of sound in liquids and solids.**—Sound is also propagated in liquids. When two stones are struck against each other under water, the shock is distinctly heard on the bank ; and a diver at the bottom of the water can hear the sound of voices on the shore. Fish can be called to be fed by whistling.

The conductivity of solids is such that the scratching of a pen at the end of a long wooden rod may be heard at the other end. In like manner, if a person whispers at the end of a long fir pole, he is heard by a person whose ear is applied against the other end, while a person who is near hears nothing. The earth conducts sounds so well that when the ear is applied to the ground the sound of horses' hoofs, the discharge of cannon, or other noise at great distances, can be perceived when they cannot be heard through the air.

In the manufacture of telegraph-wires, miles of the wire are stretched on the ground ; if one end is filed, the noise is distinctly heard at the other, especially when it is held in the ears or mouth.

In mines the sound of the workmen's blows is heard at great distances. In some of those in Cornwall which are at a distance under the sea the beating of the waves and the rattling of stones are heard, being communicated through the ground. Soldiers and hunters apply the ear to the ground to detect the distant steps of the enemy, or of game.

An interesting example of the good conductivity of solids for sound is afforded by the *string telephone* (fig. 183). A piece of wet bladder, D, is tightly tied over a sort of flat wooden box, B, in the

bottom of which is fitted a stout wooden tube, T, open at both ends, by which it can be fixed in a holder. A mouthpiece, M, is firmly fitted over the membrane, D; in the middle of this membrane a thin piece of ebonite is fixed by sealing-wax, and to this a string, S, with a hook, is attached. Two such apparatus are connected by a tightly stretched string attached to the hooks. If one of the mouthpieces be then spoken into, the membrane is set in vibration, and the vibrations are transmitted to the other membrane, which is also made to vibrate, so that a person holding his ear to the latter distinctly hears what is spoken even at a distance of some hundred yards.

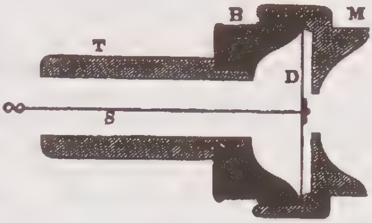


Fig. 183.

It is not necessary that sound should reach the organ of hearing through the air; it may be transmitted directly to the nerves of the ear by means of the solid parts of the body. If the ears are closed by the fingers, and the above-mentioned rods held between the teeth, the scratching of the pen is heard distinctly. If, too, a metal poker is fastened to a string the ends of which are coiled round the forefingers, which are made to close the ears, and if the poker is then struck by another body, the sound is heard with great strength in the ears.

Wheatstone's '*invisible concert*' was produced by means of four long rods of pine-wood passed from the cellar of a house through the ceilings to an upper story. These were severally connected at the bottom with a piano, violin, violoncello, and clarionet, which, being played, produced in the upper room the curious effect of an invisible concert.

That the report of cannon has been heard at a distance of over 100 miles, while the most violent thunderstorm is not heard at more than twelve to fourteen miles, is, no doubt, due to the fact that the conductivity of the earth for sound is greater than that of air.

175. **Velocity of sound in air.**—Numerous phenomena show that sound requires a certain time to pass from one place to another. Thus, if we watch a woodman felling trees at a distance, we see the axe fall, but only hear the sound a moment or two afterwards. It looks, indeed, as if the sound were due to the tearing away of the axe from the tree. In like manner, when a gun is fired, the

report is heard after the flash of light is seen. The steam issuing from the whistle of a locomotive is seen before the sound is heard; but the most striking example is that of thunder, which is only heard some time after the lightning is seen, although in the cloud both thunder and lightning are produced simultaneously.

The velocity of sound was determined experimentally by the members of the Bureau of Longitude of Paris in June 1822, during the night. A cannon was placed on a hill at Montlhéry, near Paris, and another on a plateau near Villejuif. The distance of the two places was carefully measured, and was found to be 61,045 feet, and a gun was fired at each station twelve times at intervals of ten minutes. By means of accurate watches, observers placed near the guns noted the time which elapsed between the appearance of the flash and the moment at which the sound was heard; and the mean of the observations gave the number 54·6 seconds. This was the time which the sound required to travel from one station to the other; for we shall afterwards see (329) that the velocity of light is such that the time it requires to traverse the above distance is inappreciable. Hence by a simple calculation we find that sound travels 1,118 feet in a second.

The above observations were made when the air was at a temperature of 16°. At a lower temperature the velocity of sound is less.

From some accurate experiments made near Utrecht by the above method, the velocity of sound was determined to be 1,093 feet per second in dry air at zero. Its velocity increases about 2 feet per second for every degree Centigrade. So that at 15° C., which is the ordinary temperature, the velocity of sound is about 1,120 feet per second. The exact relation between the velocities of sound at 0° C. (v_0) and at $t°$ (v_t) is $v_t = v_0\sqrt{1 + at}$, where a is the coefficient of expansion of air (245).

A laboratory method of determining the velocity of sounds consists in using a metronome (67) which is beating slowly, and is approached to a wall until a position is found at which the echo of one beat coincides with the sound of another heard directly. The distance from the wall is then half the distance which sound traverses in the interval between two beats of the metronome.

A knowledge of the velocity of sound enables us in some cases to measure distances. Thus, suppose we want to know the distance at which a gun is fired, the report of which we only hear 15 seconds after seeing the flash. As sound travels at 1,120 feet

in a second, it must traverse 16,800 feet in the time mentioned, and this would be the distance at which the gun was fired. In the same manner we may calculate the depth of a well from the number of seconds which elapse between the moment at which a stone is allowed to fall into it and that at which the sound is heard. The calculation is, however, more complicated, for the time which the body requires in falling has to be taken into account.

Knowing also the time that elapses between the moment of seeing a flash of lightning and that of hearing the thunder, we can determine the distance at which the electric discharge takes place.

An instructive illustration of the time required for the transmission of sound is afforded by observing a long column of soldiers beginning to march to the beat of drummers placed at the head. A wave-like motion, which begins with the drummers, is seen to pass along the whole line. This is owing to the fact that all the soldiers do not begin the new step at exactly the same instant; those that are behind hear the beat of the drums later than those in front.

The velocity of sound is not the same in different gases; it is greater in those which are less dense. The velocity varies inversely as the square root of the density. Dulong found the velocity at zero to be 846 feet per second in carbonic acid, 1,040 feet in oxygen, 1,093 in air, 1,106 in carbonic oxide, and 4,163 feet in hydrogen.

The velocity of sound is independent of atmospheric pressure, and is the same in air for all sounds, whether strong or weak, grave or acute. For this reason the tune played by a band is heard at a great distance without alteration, except in intensity, which could not be the case if some sounds travelled more rapidly than others.

176. **Velocity of sound in liquids and in solids.**—We have already seen that liquids conduct sound; they even conduct it better than gases. The velocity of sound in water was investigated in 1827 by Colladon and Sturm. They moored two boats, B (fig. 184), at a distance of about eight and a half miles apart in the Lake of Geneva. The first supported a bell, C, immersed in water, and a bent lever, *a*, provided at one end with a hammer, *b*, which struck the bell, and at the other with a lighted wick, *e*, so arranged that it ignited some powder, *m*, the moment the hammer struck the bell. To the second boat was affixed an ear-trumpet, the bell, *gfk*, of which was in water, while the mouth, *o*, could be applied to

the ear of the observer, so that he could measure the time between the moment when the flash of light was seen and the arrival of sound by the water. By this method the velocity was found to be 4,708 feet in a second at the temperature 8°, or four times as great as in air. This number agrees very well with that deduced from theoretical considerations, which is 4,726 feet per second.

That sound travels more rapidly in solids than in air is easily shown. If a person holds his ear against one end of a tolerably long iron bar, while another person gives a hard blow at the other end, two distinct sounds are heard; the first transmitted by the

Fig. 184.

metal, and the other transmitted by the air. Biot made an experiment of this kind, with an empty iron water-pipe over a thousand yards in length, and found that the time which sound required to travel in the iron was one-ninth of that required to travel through the air of the pipe; in other words, that the velocity in iron was nine times as great as in air.

Indirect methods only can be used for determining the exact velocity of sound in solids. The following velocities are given by various observers, in feet per second: leather 1,310; lead 4,730; cotton tape, 4,300; cardboard, 8,200; tissue paper, 8,860; oak, 10,900; copper, 12,020; pine, 15,220; steel and glass, 17,300.

177. **Reflection of sound.**—We have seen that sound is propa-

gated in air by means of spherical waves, which are developed about the sonorous body in all directions. So long as these sound-waves are not obstructed in their motion they are propagated in the form of concentric spheres ; but when they meet with an obstacle, they follow the general law of elastic bodies—that is, they are repelled like an ivory ball which strikes against a wall ; they return upon themselves, forming new concentric waves, which seem to emanate from a second centre on the other side of the obstacle. The phenomenon constitutes the *reflection of sound.*

The reflection of sound, or rather of sound-waves, follows the same laws as the reflection of heat and of light, which we shall afterwards have to explain (227, 332).

The reflection of sound may be demonstrated by means of the arrangement represented in fig. 185, which consists of two parabolic

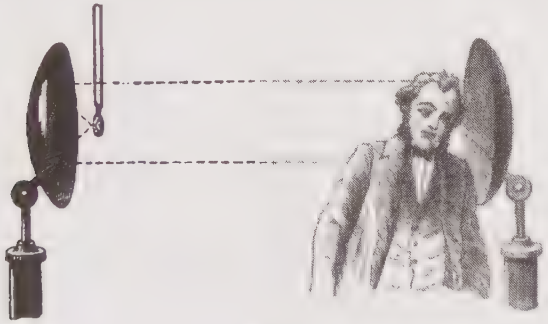


Fig. 185.

mirrors placed at some distance opposite each other. At a certain position in front of one of them, called the *focus*, is placed a watch or other convenient sounding body. It is a property of this position, the focus, that all sound-rays starting from it which fall on the adjacent mirror are reflected as parallel rays. If these parallel rays fall on the second mirror, they are reflected to *its* focus, so that if the ear be placed there, the sound-waves are concentrated in the ear, and the ticking of the watch is distinctly heard, which is not the case if the ear is in a different position. The hollow of the hand held behind the ear helps to concentrate sound, as may be seen in almost any ordinary assembly of listeners. The smooth surface of water powerfully reflects sound ; the barking

of a dog has been heard at a distance of some miles across a still lake.

As the laws of the reflection of sound are the same as those of the reflection of light and heat, curved surfaces of common occurrence often produce *acoustic foci*, like the luminous and calorific foci produced by mirrors. If a person standing under the arch of a bridge speaks with his face turned towards one of the piers, the sound is reproduced near the other pier with such distinctness that a conversation can be kept up in a low tone which is not heard by any one standing in the intermediate space.

There is a square room with an elliptical ceiling on the ground floor of the Conservatoire des Arts et Métiers, in Paris, which presents this phenomenon in a remarkable degree, when persons stand in the two foci of the ellipse. So also bellying sails, such as those in fig. 15, are often found to act like mirrors (fig. 185) in concentrating sound from a distance in a focus.

Whispering-galleries are formed of smooth walls, having a continuous curved form. The mouth of the speaker is presented at one point, and the ear of the hearer at another and distant point. In this case, the sound is successively reflected from one point to another until it reaches the ear. In the whispering-gallery of St. Paul's Cathedral the faintest sound is thus conveyed from one side of the dome to the other, but is not heard at any intermediate points. Placing himself close to the upper wall of the Colosseum, a circular building 130 feet in diameter, Wheatstone found a word to be repeated a great number of times. The Ear of Dionysius, in the quarries of Syracuse, concentrates the waves of sound similarly in one point.

It is not merely by solid surfaces, such as walls, rocks, etc., that sound is reflected, but whenever a sound-wave passes from a medium of one density into another of different density it undergoes partial reflection. In some cases the reflected wave is strong enough to produce an echo, and it always distinctly weakens the direct sound.

Different parts of the earth's surface are unequally heated by the sun, owing to the shade of trees, the evaporation of water, and other causes, so that in the atmosphere there are numerous ascending and descending currents of air of different densities. This produces, as Tyndall observed and confirmed by experiments, a condition of the atmosphere which bears much the same relation to sound that cloudiness does to light. The streams of air differently

heated, or charged with aqueous vapour to varying extents, render the atmosphere, as it were, *flocculent* to sound. Air, which is, apparently, quite transparent to light, may, owing to the occurrence of what are in effect *acoustic clouds*, be more or less opaque to sound. Ordinary rain, snow, hail, and fog have no sensible effect in obstructing sound. In these phenomena we, no doubt, have the reason, as Humboldt observed, why sound is heard farther at night than in the daytime; even in the South American forests, where the animals, which appear silent by day, fill the atmosphere in the night with thousands of confused sounds. To this may also be added that at night and in repose, when other senses are at rest, that of hearing becomes more acute.

178. **Refraction of sound.**—Not only can sound be reflected, but it can also be *refracted*, as is shown by an experiment of

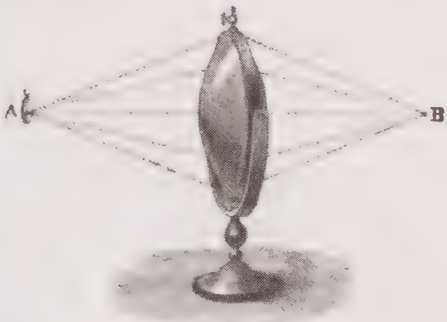


Fig. 186.

Sondhauss. On the two edges of a sheet-iron ring, a foot in diameter, two sheets of collodion are fixed (fig. 186), and the apparatus is then inflated by carbonic acid, so that it forms a double *convex* lens (360). A watch being placed at a point in the axis, a corresponding point could be found on the other side at which the ticking was heard most distinctly. Outside this point it was scarcely perceptible. Now, the sound, passing from air through the denser medium, had been made to converge towards the axis, as in the case of light (361); its direction had been changed; it had been refracted. If the apparatus were filled with hydrogen, which is lighter than air, no such focus could be found; it would act like a double concave lens (360), the divergence of the rays being

increased. This experiment may also be simply made by means of the small india rubber toy balloon.

179. **Echoes and resonance.**—An *echo* is the repetition of a sound in the air caused by its reflection from some more or less distant obstacle. Thus, if a few words are loudly spoken at a certain distance from a wood, a rock, or a building, it usually happens that, after a brief interval, the same phrase is heard repeated, as if spoken in the distance by another person ; this is due to sound-waves reflected by the obstacle. There must, however, be a certain minimum distance between the place at which the sound is produced and that at which it is reflected.

A very sharp, quick sound can produce an echo when the reflecting surface is 55 feet distant ; but for articulate sounds at least double that distance is necessary, for it may be easily shown that no one can pronounce or hear distinctly more than five syllables in a second. Now, as the velocity of sound at ordinary temperatures may be taken at 1,120 feet in a second, in a fifth of that time sound would travel 224 feet. If the reflecting surface is 112 feet distant, sound would travel through 224 feet in going and returning. The time which elapses between the articulated and the reflected sound would therefore be the fifth of a second, the two sounds would not interfere, and the reflected sound would be distinctly heard. A person speaking with a loud voice in front of a reflecting surface at the distance of 112 feet can only distinguish the last reflected syllable ; such an echo is said to be *monosyllabic*. If the reflector were at a distance of two or three times 112 feet, the echo would be *dissyllabic*, *trisyllabic*, and so on.

Multiple echoes are those which repeat the same sound several times ; this is the case when two opposite surfaces (for example, two parallel walls) successively reflect sound. There are echoes which repeat the same sound 20 or 30 times. An echo in the château of Simonetta, in Italy, repeats a sound 30 times. At Woodstock there is one which repeats from 17 to 20 syllables. Near Verdun is an echo formed by two parallel towers, at a distance from each other of about 164 feet. A person placing himself between them, and speaking a word with a loud voice, hears it repeated a dozen times. Echoes usually modify sound ; some repeat it with noise ; others with a mocking, laughing tone, or a plaintive accent.

The reflection of sound, and the production of the echo of a fog-horn, for example, have been utilised as a means of detecting the

neighbourhood of icebergs, when, owing to fogs, they cannot be seen; the principle is also applied in discovering the distance of blocks or stoppages in the underground tubes used for the pneumatic post (154). A sound is produced at the open end, and the time accurately noted which elapses before the reflection is heard; the distance of the block is then approximately half that which sound would travel in this time.

We have seen that when the distance at which a sound is reflected is 112 feet, an echo is produced; and the question may be asked, What happens when the distance is less than this? As the sound has then a smaller distance to traverse, both in going and coming, than 112 feet, it follows that the reflected sound is added to the directly-spoken one. When the reflecting surface is not far from the source of sound, as in the case of a sounding-board over the head of a preacher in a church, the direct and reflected waves reach the ear of a person at a distance at practically the same instant, and the sound is strengthened. But when the distance of the source from the reflecting surfaces is greater, as, for instance, when a person is speaking in a large empty room, the *reverberation* from the walls and ceiling produces a confused effect, since the reflected waves reach the ear an appreciable time after the direct waves. Tapestry and hangings deaden the sound by breaking up the sound-waves and preventing reflection.

The presence of an audience in an enclosed space may also render it possible to hear speaking, where without an audience the distinctness of the direct voice is destroyed by its echoes.

The case is cited of a church in which the voice of the preacher is heard quite distinctly only once a year; at Christmas—that is to say, when the reverberation is diminished owing to the walls being covered with decorations.

180. **Causes which influence the strength of sound.**

i. *The strength of sound is inversely proportional to the square of the distance of the sounding body from the ear.* This law has been deduced by calculation, but it may be also demonstrated experimentally. Let us suppose several sounds of equal strength—for instance, bells of the same kind, struck by hammers of the same weight, falling from equal heights. If four of these bells are placed at a distance of 20 yards from the ear, and one at a distance of 10 yards, it is found that the single bell produces a sound of the same intensity as the four bells struck simultaneously. Consequently, for double the distance, the intensity of the sound is only one fourth.

The distance at which sounds can be heard depends on their loudness. The report of a volcano at St. Vincent was heard at Demerara, 300 miles off, and the firing at the battle of Waterloo was heard at Dover, while the report of the colossal volcanic outburst at Krakatoa in 1882 is said to have been heard at a distance of 2,900 miles.

ii. *The strength of sound increases with the amplitude of the vibrations of the sounding body, and varies as the square of the amplitude* (185). The connection between the intensity of the sound and the amplitude of the vibrations is readily observed by means of vibrating cords. For if the cords are somewhat long, the oscillations are perceptible to the eye, and it is seen that the sound is feebler in proportion as the amplitude of the oscillations decreases.

For the same reason the dying sounds of the last blows of a bell become gradually feebler, until they are ultimately extinguished.

iii. *The strength of sound depends on the density of the air in the place in which it is produced.* As we have already seen (173), when an alarum moved by clockwork is placed under the bell-jar of the air-pump, the sound becomes weaker in proportion as the air is rarefied.

In hydrogen, which has about $\frac{1}{14}$ the density of air, sounds are much feebler, although the pressure is the same. In carbonic acid gas, on the contrary, which is half as heavy again as air, sounds are louder. On very high mountains, where the air is much rarefied, it is necessary to speak with some effort in order to be heard, and the discharge of a gun produces only a feeble sound. During a frost, sounds are heard at a greater distance, because air is then more dense and usually more homogeneous; and country people will thus often predict the weather from observing the sound of the village bell. For the propagation of sound is modified, as we have seen (177), by the occurrence of layers of air of different densities.

iv. *The strength of sound is modified by the motion of the atmosphere and the direction of the wind.* In calm weather sound is always better propagated than when there is wind; in the latter case, for an equal distance, sound is louder in the direction of the wind than in the contrary direction.

v. *The strength depends also on the size of the body set in vibration.* Thus a long, heavy whip can be made to crack more

loudly than a short and light one, since in the former case a larger mass and a greater volume of air are put in motion ; the sound of a large bell exceeds that of a small one ; the report of a cannon is louder than that of a gun.

vi. Lastly, *sound is strengthened by the neighbourhood of a resonant body.* A string made to vibrate in free air has but a very feeble sound ; but when it vibrates in contact with a sounding-box, as in the case of the violin, the guitar, the violoncello, or the pianoforte, its sound is much stronger. This arises from the fact that the box, and the air which it contains, vibrate in unison with the string. Hence the use of sounding-boxes in these instruments.

181. **Influence of tubes on the transmission of sound.**—The diminution in the strength of sound as the distance increases is due to the fact that the sound-waves are propagated in the form of continually increasing spheres ; and it may indeed be proved geometrically that, since sound is thus transmitted, its intensity must be inversely as the square of the distance from the source of sound. If, however, the sound is sent through a tube, the waves are propagated in only one direction, and sound can be transmitted to great distances without appreciable alteration. Biot found that in one of the Paris water-pipes, 1,040 yards long, the voice lost so little of its intensity that a conversation could be kept up at the ends of the pipe in a very low tone ; so that, as Biot expressed it, in order not to be heard it was necessary *not to speak at all.* The weakening of sound becomes, however, perceptible in tubes of large diameter, or where the sides are rough.

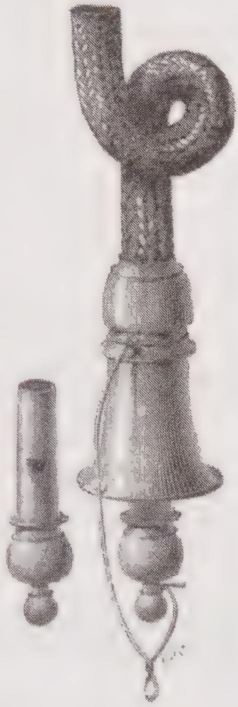


Fig. 187.

In Carisbrooke Castle, in the Isle of Wight, there is a well, lined with smooth masonry, 212 feet deep and 12 feet wide ; when a pin is dropped into the well, it is distinctly heard to strike

against the water ; shouting or coughing into this well produces a resonant ring of some duration.

This property of transmitting sounds was first applied in England for *speaking-tubes*, which are used in mines, in hotels, and large establishments, for transmitting orders. They consist of india rubber or metal tubes of small diameter, provided at each end with an ivory, bone, or ebonite mouthpiece, and passing from one room to another. If a person speaks at one end of the tube (fig. 187), he is distinctly heard by a person applying his ear at the other end. Usually the main part of the tube is of zinc, and the part to which the mouthpiece is attached of india rubber.

A whistle can be placed in the mouthpiece, in order to call the attention of the person signalled for ; the person at one end blows into the open tube, which sounds the whistle at the other end ; the person signalled to then removes the whistle and applies his ear, while the other end is spoken into.

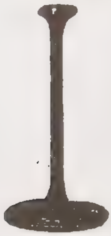


Fig. 188.

One of the most important applications of acoustic principles is that of the ***stethoscope***. It consists of a cylinder of hard wood, about 1 foot long, and 1½ inch broad at one end, in which a longitudinal passage is bored (fig. 188). One end of the stethoscope is held against the part of the body to be examined, and the ear is held against the other. The skilled physician can detect the healthy or diseased condition of an organ by the peculiar sound emitted.

182. **Speaking-trumpets.**—The *speaking-trumpet*, as its name implies, is used to render the voice audible at great distances. It consists of a slightly conical tin or brass tube (fig. 189) very wide or funnel-shaped at one end (which is called the *bell*), and provided

Fig. 189.

with a mouthpiece at the other. The larger the dimensions of this instrument, the greater is the distance at which the voice is heard. Its action is usually ascribed to the successive reflection of sound-waves from the sides of the tube, by which the waves tend more

and more to pass in a direction parallel to the axis of the instrument. It has, however, been objected to this explanation, that the sounds emitted by the speaking-trumpet are not stronger solely in the direction of the axis, but in all directions; and that the bell would not tend to produce parallelism in the sound-wave, whereas it certainly exerts considerable influence in strengthening the sound. According to Hassenfratz, the bell acts by causing a large mass of air to be set in consonant vibration before it begins to be diffused. By means of the speaking-trumpet, the word of command can be heard on board ship above the noise of the waves. The longer the trumpet, the greater the distance to which sound is carried. A strong man's voice sent through a trumpet 20 feet in length has been heard at a distance of three miles, while without such help about 900 or 1,000 feet is the greatest distance at which he can be heard.

183. **Ear-trumpet. Audiphone.**—The ear-trumpet is used by persons who are hard of hearing, and consists of a metal tube, one

Fig. 190.

of the ends of which, terminating in a *bell*, receives the sound, while the other end is introduced into the ear. Fig. 190 shows a variety of different shapes. The action of this instrument is the reverse of that of the speaking-trumpet. The bell serves as mouthpiece—that is, it receives the sounds coming from the person who speaks. These sounds are transmitted by a series or

reflections to the interior of the trumpet, so that the waves, which would become greatly dispersed, are concentrated on the hearing apparatus, and produce a far greater effect than divergent waves would have done.

In man and many animals the outer ear is a trumpet which receives the waves of sound. In some animals this part of the hearing apparatus is long and flexible, so that, by adjusting it, the animal can easily recognise the direction from which the sound proceeds. From this is, no doubt, derived the common phrase 'pricking up the ears.'

Here may be mentioned the ***audiphone***, invented by Mr. Rhodes, of Chicago, an instrument which is of considerable service

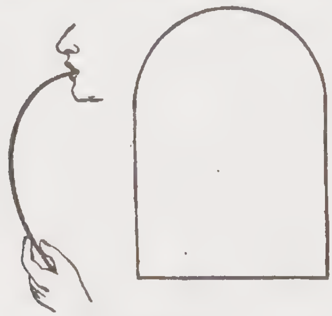


Fig. 191.

to people hard of hearing; in its most simple form (fig. 191) it consists of a rectangular piece of smooth cardboard or sheet ebonite about $\frac{1}{16}$ of an inch in thickness, the square end of which is held in one hand, while the opposite and convex edge is pressed against the teeth of the upper jaw so that it is slightly bent: it receives the sounds which are produced in the air, and transmits them to the auditory nerves through the bones of the head. It is stated that, by means of this simple apparatus, not merely deaf people, but even those who are deaf and dumb, can hear musical sounds and even speech.

CHAPTER II

MUSICAL SOUNDS. PHYSICAL THEORY OF MUSIC

184. **Difference between musical sounds and noise.**—Sounds are distinguished from *noises*. Sound, properly so called, or *musical sound*, is that which produces a continuous and regular sensation, and the rate of whose vibrations can be determined. The only condition necessary for producing a musical sound is that the individual impulses shall succeed each other with sufficient rapidity at equal intervals of time. Whatever be its origin, whether it be the ticks of a watch or the puffs of a locomotive, if this condition be fulfilled, the coalescence of the separate impressions produces a musical sound.

On the other hand, noise is either a sound of so short a duration that it cannot be determined, in which case it is called a *report*, like that of a cannon, or else it is a confused mixture of many discordant sounds, like the rolling of thunder, the rattling of a box of nails, the hissing of hot iron when dipped in water, the rustling of the leaves, the splashing of a falling jet, or the noise of the waves. The difference between sound and noise is, however, by no means sharp. Savart, a French physicist, has shown that there are relations of height in the case of noise, as well as in that of musical sound, and there are said to be certain ears sufficiently well organised to determine the musical value of the sound produced by a carriage rolling over the square blocks of a granite pavement.

The action of a noise upon the ear has been compared to that of a flickering light upon the eye ; both are painful, in consequence of the sudden and abrupt changes which they produce in the respective nerves on which they act.

185. **Characteristics of musical sounds.**—Musical sounds or tones have three leading qualities—namely, *pitch*, *intensity*, and *timbre*, *colour*, or *quality*.

i. The *pitch* or *frequency* of a musical tone is determined by the

number of vibrations in a second yielded by the body producing the tone.

ii. The *intensity* or *loudness* of the tone depends on the *extent* or *amplitude* of the vibrations. It is greater when the extent is greater, and less when it is less. So far it has not been possible to get any experimental measurement of loudness, but it seems to be nearly proportional to the square of the amplitude of the vibrations which produce the tone.

iii. The *timbre* (the French word for 'stamp') is that peculiar quality of tone which distinguishes a note when sounded on one instrument from the same note when sounded on another. Thus, when the C of the treble stave is sounded on a violin and on a flute, the two notes will have the same pitch—that is, are produced by the same number of vibrations per second; and they may have the same intensity or loudness, and yet the two notes will have very distinct qualities—that is, their timbre is different. By some writers this peculiar property is called the *colour*, by others the *quality*, of a tone.

186. **Siren.**—The vibrations of any sounding body are so rapid that they cannot be followed by the eye and counted.

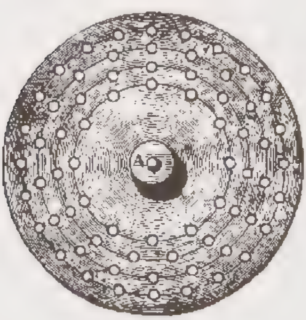


Fig. 192.

Various forms of apparatus have been invented for the purpose of determining the number of vibrations corresponding to particular notes. Of these, the one represented in fig. 192, devised by Seebeck, is given as being the simplest and most intelligible. It consists of a circular disc of stout cardboard, or of sheet metal, about 1 foot in diameter. This disc is perforated by four concentric series of small, equidistant holes. For simplicity's sake the inner of these is represented as having 12, the second 15, the third 18, and the fourth 24 holes; but a multiple of these ratios—say 48, 60, 72, and 96—is more convenient.

The disc is made to rotate rapidly, and the most convenient plan is to fit it on a turning-table (fig. 18), in the place of A B. Then, by means of a glass tube, drawn out at one end so as to be smaller than the diameter of the holes, a current of air is directed

against one of the series of holes in the rotating disc. A tone is now heard, which is tolerably pure when the rotation is sufficiently rapid, and the number of vibrations corresponding to it can be readily determined. Suppose, for instance, that there are 48 in the inner series of holes. Then each time a hole passes in front of the glass tube a wave is produced which reaches the ear in the ordinary manner. If, for example, the disc makes 16 turns in a second, in each second 16 times 48, or 768, holes pass in front of the tube, and there are produced 768 waves, which fall upon the ear within a second, at equal intervals of time. If, in like manner, the tube were held over the second series of holes, while the rotation goes on at the same rate, we should hear the tones corresponding to 16 times 60, or 960 vibrations in a second. Thus, proceeding in like manner, and moving the tube successively from the inner to the outer series of holes, we hear successively the fundamental note, the major third, the fifth, and the octave (189).

187. **Limit of perceptible sounds.**—Savart was the first to determine the limit of the number of vibrations which the ear

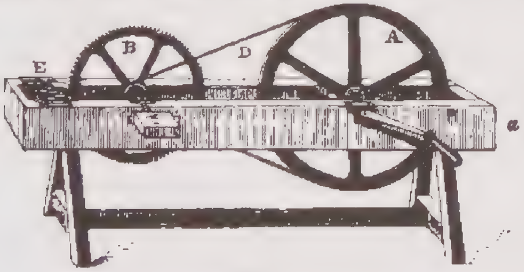


Fig. 193.

could perceive. He invented an apparatus for this purpose which is known as *Savart's toothed wheel* (fig. 193). It consists essentially of a metal wheel, B, with a series of equidistant, sharp teeth on its periphery. This is made to rotate at a uniform speed by the motion transmitted by a band, D, from a large wheel, A, and a card, or, still better, a thin elastic steel plate, E, is fixed so that, in the rotation of the wheel, each of the teeth strikes against the plate, and each time produces a sound. If, for instance, the rim of the wheel has 600 teeth, and it is made to rotate 4 times in a second, 2,400 impulses are given in a second. The number of

impulses depends thus on the velocity of rotation, and the sounds produced are pure and continuous.

Thus, to determine the number of vibrations corresponding to any particular note it is simply necessary to turn the wheel at an increasing rate until it produces a note in unison (189) with the one in question, after which the speed of rotation is kept constant. Knowing the number of teeth on the wheel, and the rate of rotation, which is ascertained by a clockwork motion on the side, we can at once calculate the number of vibrations. By means of this apparatus, Savart ascertained that the deepest audible sounds are produced by 16 vibrations in a second. If the number of vibrations is less, no continuous sound is heard. The same physicist found that the highest sound which the ear can perceive corresponds to 48,000 vibrations in a second. Between these two limits it will be seen what an enormous quantity of sounds may be produced and perceived. Yet the sounds used in music, and more especially in singing, are comprised within much narrower limits (192). Thus, the range of vibrations produced by the human voice has been ascertained ; and it has been found that the lowest notes of a man's voice are made by 190 vibrations in a second, and the highest notes by 678. The lowest of note a woman's voice corresponds to 572 vibrations, and the highest to 1,606.

188. **Musical scale. Gamut.**—The human ear can distinguish, not merely that which is the highest or the lowest among several sounds, but it can also appreciate the relations which exist between the numbers of vibrations corresponding to each of these sounds. Not, indeed, that we can say whether one sound produces two or three times as many vibrations as another ; but whenever the numbers of vibrations of two successive or simultaneous sounds are in a simple ratio, these sounds excite in us an agreeable sensation, which varies with the ratio of the vibrations of the two sounds, and which the ear can readily estimate. Hence results a series of sounds characterised by relations, which have their origin in the nature of our organisation, and which constitute what is called the *musical scale.*

This is the ordinary opinion as to the origin of the musical scale. According to Helmholtz, however, the system of scales, and their harmonic relation, does not depend on invariable natural laws, but is, on the contrary, the consequence of æsthetic principles which have varied with the progressive development of humanity, and will continue to vary.

In this series the sounds are reproduced in the same order, in periods of seven, each period constituting the *diatonic scale* or *gamut*; and the seven sounds or *notes* of each gamut are designated by the names C, D, E, F, G, A, B, or by *ut* or *do*, *re*, *mi*, *fa*, *sol*, *la*, *si*. The first six of these letters are from the first syllables of the lines of a hymn which was sung by the chorister children to St. John, their patron saint, when they prayed to be freed from hoarseness; and the word *si* is formed of the first letters of St. John's name.

Ut queant laxis	resonare fibris
Mira gestorum	famuli tuorum
Solve polluti	labii reatum
Sancte	Ioannes.

The word gamut is derived from *gamma*, the third letter of the Greek alphabet, because Guido d'Arezzo, who first (in the eleventh century) represented notes by points placed on parallel lines, denoted these lines by letters, and chose the letter gamma to designate the first line.

If we agree to represent by 1 the number of vibrations of the fundamental note C or *do* of the gamut—that is to say, of the lowest note—experiment shows that the numbers of vibrations of the other notes of the scale are those given in this table :—

C	D	E	F	G	A	B	*c*
do	*re*	*mi*	*fa*	*sol*	*la*	*si*	*do*
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2

This table does not give the absolute numbers of the vibrations of the various notes, but only their relative numbers. Knowing the absolute number of vibrations of the fundamental C, we may deduce those of the other notes by multiplying them by $\frac{9}{8}, \frac{5}{4}, \frac{4}{3}, \ldots$ or 2 respectively; and we thus find that the number of vibrations of the octave (189) is double that of the fundamental note.

The scale may be continued by taking the octaves of these notes, denoting them by *c*, *d*, *e*, *f*, *g*, *a*, *b*, and again the octaves of these last, and so forth.

189. **Intervals.**—The *interval* between two notes is the ratio of the numbers of vibrations which produce these notes.

The interval between any two consecutive notes of the gamut is called a *second*—such as the interval from *do* to *re*, from *re* to *mi*, from *mi* to *fa*, and so on.

If between any two notes which are compared there are one, two, three, four, five, or six intermediate notes, these intervals are called respectively a *third*, a *fourth*, *fifth*, *sixth*, *seventh*, and *octave*. These words are not used in the same sense as in fractional arithmetic; an interval of a fifth simply stands for the *difference* of pitch between the first and fifth notes of the scale. Thus the interval from C to E is a third, that from C to F a fourth, from C to G a fifth, from C to A a sixth, from C to B a seventh, and from C to *c* an octave.

Although two or more notes may be separately musical, it does not follow that, when sounded together, they produce a pleasant sensation. When the ear can distinguish without fatigue the ratio between two sounds, which is the case when the ratio is simple, the accord or co-existence of these two sounds forms a *consonance*; but if the number of vibrations is in a complicated ratio, the ear is unpleasantly affected, and we have *dissonance*.

The simplest concord is *unison*, in which the numbers of vibrations are equal; then comes the octave, in which the number of vibrations of one sound is double that of the other; then the fifth, where the ratio of the sounds is as 3 to 2; the fourth, of which the ratio is 4 to 3; and, lastly, the third, where the ratio is 5 to 4.

If three notes are sounded together, they are concordant when the numbers of their vibrations are as 4 : 5 : 6. Three such notes form a *harmonic triad*, and if sounded with a fourth note, which is the octave of the lowest, they constitute what is called a *major chord*. Thus C, E, G form a major triad, G, B, *d* form a major triad, and F, A, *c*, form a major triad. C, G, and F have, for this reason, special names, being called respectively the *tonic*, *dominant*, and *sub-dominant*, and the three triads the *tonic*, *dominant*, and *sub-dominant* triads or chords respectively.

If, however, the ratio of any three notes is as 10 : 12 : 15, the three sounds are slightly dissonant, but not so much as to prevent them from producing a pleasant sensation. When these three notes, and the octave to the lowest note, are sounded together, they constitute a *minor chord*.

The intervals between the notes in the scale are—

C to D $\frac{9}{8}$	G to A $\frac{10}{9}$
D to E $\frac{10}{9}$	A to B $\frac{9}{8}$
E to F $\frac{16}{15}$	B to C $\frac{16}{15}$
F to G $\frac{9}{8}$	

It will be seen that there are here three kinds of intervals: the interval $\frac{9}{8}$ is called a *major tone*, and that of $\frac{10}{9}$ a *minor tone*; the relation between the major and the minor tone is $\frac{9}{8} : \frac{10}{9} = \frac{81}{80}$, and is called a *comma*. The interval $\frac{16}{15}$ is called a *major semitone*. The major scale is formed of the following succession of intervals: a major tone, a minor tone, a major semitone, a major tone, a minor tone, a major tone, and a major semitone. It is this succession which constitutes the scale: the key-note, or the tonic, may have any number of vibrations; but, once its height is fixed, that of the other notes is always in the above ratio.

190. **On semitones and on scales with different key-notes.**—It is found convenient for the purpose of music to introduce notes intermediate to the seven notes of the gamut; this is done by increasing or diminishing those notes by an interval of $\frac{25}{24}$, which is called a *minor semitone*. When a note—say C—is increased by this interval, it is said to be *sharpened*, and is denoted by the symbol C♯, called 'C sharp'—that is, the ratio of C♯ to C is as 25 : 24. When it is decreased by the same interval, it is said to be *flattened*, and is represented thus, B♭, called 'B flat'—that is, the ratio of B to B♭ is as 25 : 24. If the effect of this be examined, it will be found that the number of notes in the scale from C up to *c* has been increased from seven to twenty-one notes, all of which can be easily distinguished by the ear. Thus, reckoning C to equal 1, we have—

C	C♯	D♭	D	D♯	E♭	E	etc.
1	$\frac{25}{24}$	$\frac{27}{25}$	$\frac{9}{8}$	$\frac{75}{64}$	$\frac{6}{5}$	$\frac{5}{4}$	etc.

Hitherto the note C has been taken as the tonic or *key-note*. Any other of the twenty-one distinct notes above mentioned—for instance, G, or F, or C♯, etc.—may be made the key-note and a scale of notes constructed with reference to it. This will be found to give rise in each case to a series of notes some of which are identical with those contained in the series of which C is the key-note, but most of them different. The same would be true for the minor scale as well as for the major scale, and, indeed, for other scales which may be constructed by means of the fundamental triad.

191. **On musical temperament.**—The number of notes that arise from the construction of the scales described in the last article is enormous; so much so as to prove quite unmanageable in the practice of music, and particularly for music designed for instruments with fixed notes, such as the pianoforte or harp.

Accordingly it becomes practically important to reduce the number of notes, which is done by slightly altering their just proportions. This process is called *temperament*. By tempering the notes, however, more or less dissonance is introduced, and accordingly several different systems of temperament have been devised for rendering this dissonance as slight as possible. The system usually adopted is called the system of *equal temperament*. It consists in keeping the octaves pure, but substituting between them, between C and *c*, for instance, eleven notes at equal intervals, each interval being the twelfth root of 2, or 1·05946. By this means the distinction between the semitones is abolished, so that, for example, C♯ and D♭ become the same note. The scale of twelve notes thus formed is called the *chromatic scale*. It, of course, follows that the major triad becomes slightly dissonant. Thus, in the diatonic scale, if we reckon C to be 1, E is denoted by 1·25000 and G by 1·50000. On the system of equal temperament, if C is denoted by 1, E is denoted by 1·25992 and G by 1·49831. When some of the intervals are kept pure, and the error is distributed among the others, we have *unequal temperament*.

With instruments such as the violin or violoncello it is possible to obtain all the intervals with perfect accuracy—that is, to obtain *natural* or *just temperament* ; this is also the case with the voice, where singers have been trained to sing without the accompaniment of a piano ; hence it is here that we meet with the highest musical effect.

192. **The number of vibrations producing each note. The tuning-fork.**—Hitherto we have not assigned any numerical value to that symbol the note C. In the theory of music it is common to assign 256 complete vibrations to the middle C. This, however, is arbitrary ; its justification is the facility with which this number may be subdivided. An instrument is in tune provided the intervals between the notes are correct, when C is yielded by any number of vibrations in a second, which does not differ much from 256. Moreover, two instruments are in tune with one another, if, being separately in tune, they have any one note—for instance, C—yielded by the same number of vibrations. Consequently, if two instruments have one note—say C—in common, they can then be brought into tune jointly by having their remaining notes separately adjusted with reference to that fundamental note. A *tuning-fork* is an instrument yielding a constant note, and is used as a standard for tuning musical instruments. In consists of an elastic steel

rod, bent as represented in fig. 194 or 195. It is made to vibrate either by drawing a bow across the ends, as shown in the figure, or by striking one of the legs against a hard body, or by rapidly separating the two legs by means of a steel rod. The vibration produces a note which is always the same for the same tuning-fork.

The note is strengthened by fixing the tuning-fork on a box open at one end called a *resonance-box*.

The small fork in ordinary use, represented in fig. 194, is held between the fingers at *b*, one of the prongs *c* struck smartly against a hard body and then the end *a* held on a table. The sound is thereby greatly intensified, the table acting as a *sounding-board*.

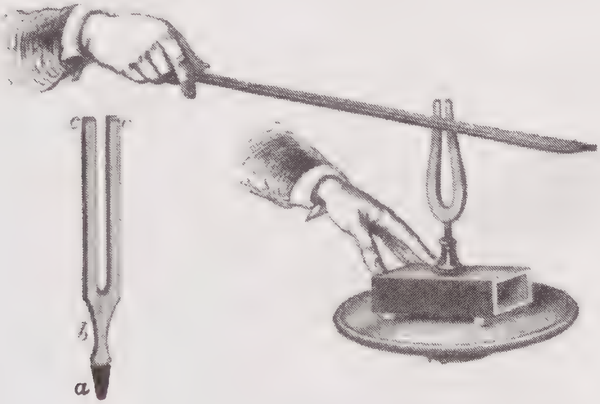


Fig. 194. Fig. 195.

It has been remarked for some years that not only has the pitch of the tuning-fork—that is, *concert pitch*—been getting higher in the larger theatres of Europe, but also that it is not the same in London, Paris, Vienna, Milan, etc. This is a source of great inconvenience to both composers and singers, and a commission was appointed to establish in France a tuning-fork of uniform pitch, and to prepare a standard which would serve as an invariable type. In accordance with the recommendations of that body, a *normal tuning-fork* has been established, which is compulsory on all musical establishments in France, and a standard was deposited in the Conservatory of Music in Paris.

It makes 870 single or 435 complete vibrations in a second, and yields the note *la* of the treble stave ; the *do*, or C, of the same stave makes thus 261 complete vibrations in a second.

The standard tuning-fork adopted by the Society of Arts in London, on the recommendation of a committee of eminent musicians, makes 264 vibrations in a second, and gives the middle C of the treble stave. The corresponding A, or *la*, gives therefore 440 vibrations in a second.

The middle C is the note sounded by the white key immediately on the left of the two black keys which are near the middle of the keyboard of a pianoforte. It is designated in musical notation as

. For purposes of comparison it is convenient to call this note c', and the next lower octave c ; the octave lower than this C, and the still lower one $C_{,}$, and so on. The lowest note of grand pianos is $A_{,,}$, which gives 27·5 vibrations in a second.

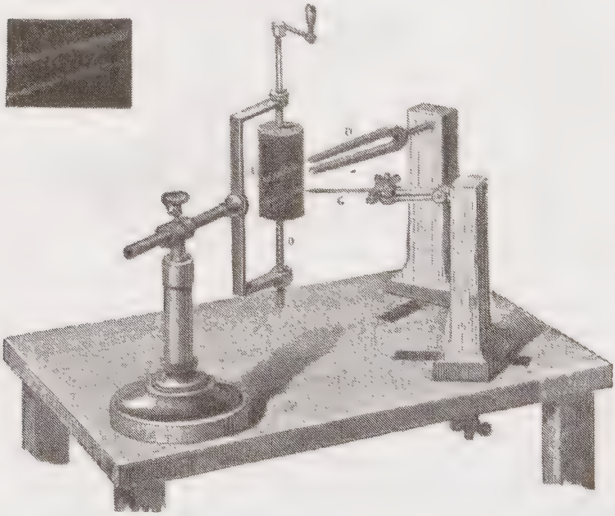


Fig. 196.

In like manner the higher octaves are distinguished by affixes—thus c'', c''', c^{iv}, and so forth. In height the pianoforte reaches to a^{iv}, with 3,520, or c^{v}, with 4,224 vibrations in a second.

The practical range of musical sound is comprised between 40 and about 4,000 vibrations in a second, or within 7 octaves.

The principle of the method by which the vibration-frequencies of two tuning-forks or those of a tuning and a vibrating rod are compared is illustrated in fig. 196. The apparatus there represented consists of a cylinder, A, which can be rotated about its axis by means of a handle. The axis has a screw-thread cut upon it, so that as the handle is turned the cylinder rises or falls. The cylinder is covered with paper coated with lamp-black. Suppose that we wish to compare the rate of vibration, or *vibration-frequency*, of a rod pointed and clamped as shown, with that of a tuning-fork. A thin copper style is attached to one prong of the fork, and the end of this, as well as the point of the rod G, is brought into contact with the cylinder. If while both are at rest the handle is turned, two parallel and slightly inclined lines will be traced on the blackened surface. But when both are set in vibration and the cylinder is rotated as uniformly as possible, each point traces a sinuous line containing as many undulations as the point—whether belonging to the tuning-fork or the rod—has made vibrations (fig. 196, top left-hand corner). Thus, by counting the number of undulations in a given distance on the cylinder made by each point and dividing one by the other, we obtain a comparison of their vibration frequencies. In the same way the vibration frequencies of two forks are compared.

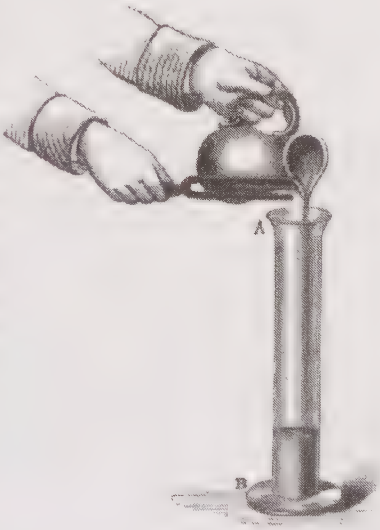


Fig. 197.

193. **Resonance of air.** The action of the resonance box in strengthening sound (fig. 195) may be illustrated by the following experiment (fig. 197). A B is a glass cylinder,

about 15 inches in height, and 1 to 1½ inch in diameter. If an ordinary tuning-fork be made to vibrate, its sound is very faint, and if it is held over the empty cylinder probably no alteration will be experienced. When, however, water slowly and noiselessly poured into the cylinder reaches a certain height, the previously faint sound is far louder. Any other tuning-fork, which yields a different note, if held over the cylinder, will not have its note strengthened. Reverting now to the original tuning-fork; if, while it is still sounding and its sound is being strengthened by its nearness to the cylinder, we continue to pour in water, the sound becomes as faint as it was originally. But if the excess of water be removed until the tone of the fork is once more strengthened, and if, removing the fork, we sound the column again by blowing across the mouth of it, we find that the column of air emits the same note as the tuning-fork. Hence, then, the tuning-fork could set a column of air in vibration so as to produce the same note; and this, adding itself to the original, strengthened it.

194. **Compound musical notes. Harmonics. Overtones.**—We have already seen (185) that there is a peculiar quality, or timbre, as it is called, by which the notes of different instruments are characterised. Thus, we readily distinguish between notes of the same pitch when sounded on a pianoforte, and on an organ or trumpet, between the note of a stretched wire and one of catgut, and even with one and the same string according as it is 'struck' as with a piano, 'twitched' as with a harp, or 'bowed' as with a violin. This peculiarity of the tone is due to the fact that only in very few cases does an instrument give a pure note, but that in most cases the fundamental note is accompanied by a series of upper notes or *harmonics*. To understand what these are we may refer to art. 206, in which it is stated that by successively intensifying the current of air we get in a stopped pipe a succession of notes the numbers of whose vibrations are as the series of odd numbers, 1, 3, 5, 7, etc. So, too, if we sound an open pipe in a similar way, we get the series of notes whose vibration frequencies are represented by the numbers 1, 2, 3, 4, 5, etc. The first of these notes being called the *fundamental*, the others are called the *harmonics* of the fundamental.

Now, if we sound a particular note on the piano, a practised ear can discover, by a little attention, that the primary or fundamental note is accompanied by a series of higher notes of varying intensities, but all faint as compared with the fundamental. These

upper notes may be detected, and the compound nature of the primary sound analysed, even by an unpractised ear, by the use of *resonance globes*, or *resonators*, which Helmholtz devised for this purpose. These instruments, one of which is represented in fig. 198, are an application of the principle explained in the foregoing paragraph. They are small, hollow spheres ; the projection *b*, which has a small hole, is placed in the ear, while the wider aperture, *a*, is directed towards the source of sound. Each of these resonators is constructed or tuned for a particular note ; so that if, having sounded the string of a pianoforte, we hold near to it a resonator tuned for a particular note, this note if present will be intensified.

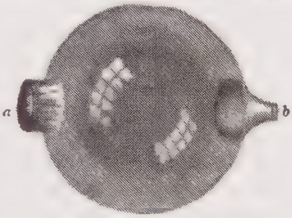


Fig. 198.

Thus, if we depress the key *c* we hear no particular strengthening if a resonator tuned for *g* be held near the ear ; but when the resonators sounded for *c'*, *g'*, *c''* are used, we hear them powerfully respond when held to the ear. Hence the notes *c'*, *g'*, *c''* are contained in the mass of sound which is produced when the key *c* is depressed.

Helmholtz's researches show that the different timbre or quality of the sounds yielded by different instruments is due to the fact that the fundamental notes are accompanied in each case by special harmonics or *overtones* in varying intensity ; some of his principal results are as follows :—

Simple notes—those, that is to say, without any admixture or overtones—are most easily produced when a tuning-fork is held near a resonance-box of suitable length. These notes are soft, and are free from all sharpness and roughness.

The notes of the *flute* are also nearly pure, for their overtones are very feeble. Stopped organ-pipes of large cross section give the fundamental note almost perfectly pure ; narrower ones give, along with it, the fifth of the octave. Wide open pipes give the octave along with the fundamental note ; and narrower ones give a series of overtones.

The overtones present in the sounds of stretched strings depend on the material of the latter and on the manner in which they are made to sound. In good *pianos* the overtones are powerful up to the sixth. In other *stringed instruments* the fundamental note is

comparatively stronger than in pianos: the first overtones are feebler; the higher, from the sixth to the tenth, on the contrary, are far more distinct, and produce the penetrating character of the sound of stringed instruments. In the pianoforte the place at which the string is struck is $\frac{1}{7}$ or $\frac{1}{9}$ of the whole length. These positions destroy the seventh and ninth harmonics respectively—*i.e.* those the vibration-frequencies of which are 7 and 9 times as great as that of the fundamental, which are discordant with each other and with the fundamental—while just those overtones preponderate which produce the most beautiful musical effect (189).

Metal rods and *plates* produce, along with the fundamental note, a series of very high overtones which are discordant with each other, but are continuous and of equal strength with the primary note. Thus is produced that peculiarity known as a *metallic sound.*

By the occurrence of the lower harmonics along with the primary note the tone is more sonorous, richer and deeper than the primary note; by the occurrence of the higher overtones, the tone acquires its penetrating character. The human voice is very rich in overtones.

The rushing sound heard when certain large shells are held near the ear is due to the fact that the mass of air in the shell responds to certain sounds and strengthens them.

CHAPTER III

TRANSVERSE VIBRATIONS OF STRINGS. STRINGED INSTRUMENTS

195. **Transverse vibrations of strings.**—We have already seen (170) that when an elastic string, stretched at the ends, is removed from its position of equilibrium, it reverts to it as soon as it is let go, making a series of vibrations which produce a sound. The strings used in music are commonly of catgut or metal wire. The vibrations which strings experience may be either *transverse* or *longitudinal*, but practically the former are alone important. *Transverse vibrations* may be produced by drawing a bow across the strings, as in the case of the violin ; or by striking the strings, as in the case of the pianoforte, or by twitching them transversely, as in the case of the guitar and the harp.

196. **Laws of the transverse vibrations of strings.**—The number of transverse vibrations which a string can make in a second—that is, its vibration-frequency (192) or pitch—varies with its length, its diameter, its tension, and with its specific gravity, in the following manner :—

The tension being constant, the number of vibrations in a second is inversely proportional to the length of the string—that is, if a string makes 18 vibrations in a second, for instance, it will make 36 if its length is one-half, 54 if its length is one-third, and so on. On this property depend the violin, the double-bass, etc. ; for in these instruments, by pressing the string with a finger, the length is reduced or increased at pleasure, and the frequency, and therewith the note, is regulated.

With strings of the same length and tension *the number of vibrations in a second is inversely as the diameter of the string*—that is, the thinner a string, the greater its frequency, and the higher its pitch. In the violin, the treble string, which is the thinnest, makes double the number of vibrations of that which would be made by a string the diameter of which is twice as great.

The number of vibrations in a second is directly proportional to the square root of the stretching weight or tension—that is, when the tension of a string is four times as great, the frequency is doubled ; when the tension is nine times as great, the frequency is trebled ; and so on. This, then, furnishes a means of altering the pitch of a note by stretching, as is done in stringed instruments.

Other things being equal, *the vibration frequency of a string is inversely as the square root of its density.* Hence, the greater the density of the material of which strings are made, the deeper are the sounds they yield.

From the preceding laws it will be seen how easy it is to vary the number of the vibrations of strings and make them yield an extreme variety of sounds, from the deepest to the highest used in music.

197. **Sonometer. Verification of the laws of the vibrations of strings.**—This may be effected by means of an instrument called

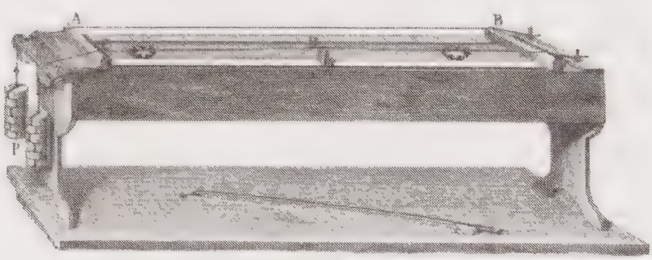


Fig. 199.

the *sonometer* or *monochord.* It consists of a thin wooden box to strengthen the sound. On this there are two fixed bridges, A and B (fig. 199), over which pass the strings, A B, C D, which are commonly metal wires. These are fastened at one end, and stretched at the other by weights, P, which can be increased or diminished at will. By means of a third movable bridge, D, the length of that portion of the wire which is to be put in vibration can be altered at pleasure.

If two strings are taken which are identical in all respects, and are stretched by equal weights, they will be found, on being struck, to yield the same sound. If now one of them be divided by the movable bridge, D, into two equal parts, the sound yielded by C D

will be the higher octave of that yielded by the entire string, A B, which shows that the number of vibrations is doubled, and thus verifies the first law.

To verify the second law, the bridge, D, is removed. If the string A B is taken so that it has double the diameter of the other, but both are stretched by the same weight, it will be found that the note which the thinner string yields is the octave above that yielded by A B ; proving thus that the frequency is doubled by halving the diameter of the string.

The two strings being of the same diameter, and the same length, if the weight which stretches the one is four times that which stretches the other, the sound yielded by the first is the higher octave of that of the second, which shows that the number of vibrations is doubled ; when the weight is nine times as great the frequency is increased threefold, and hence (189) the note is the higher octave of the fifth of the former, and so on.

The fourth law is established by using strings of different materials—copper, steel, catgut—and therefore of different densities, but of the same dimensions, and stretched to the same extent.

198. **Stringed instruments.**—Stringed musical instruments depend on the production of transverse vibrations. In some, such as the piano, the sounds are *constant*, and each note requires a separate string ; in others, such as the violin and guitar, the sounds are *varied* by the fingering, and can be produced by fewer strings. A stretched string, like other sources of sound, never vibrates exclusively as a whole, but makes at the same time partial vibrations ; and thus the fundamental note never occurs alone, but is accompanied by overtones (194), which, however, are usually too feeble to be perceived by the ear without some device for strengthening them.

In the *piano* the vibrations of the strings are produced by the stroke of the *hammer*, which is moved by a series of bent levers communicating with the keys. The sound is strengthened by the vibrations of the air near the *sounding-board* on which the strings are stretched. Whenever a key is struck, a *damper* is raised, which falls when the finger is removed from the key and stops the vibrations of the corresponding string. By means of a *pedal* all the dampers can be raised simultaneously, and the vibrations then last for some time.

The *harp* is a sort of transition from the instruments with constant to those with variable sounds. Its strings correspond to the

natural notes of the scale ; by means of the pedals the lengths of the vibrating parts can be changed, so as to produce sharps and flats. The sound is strengthened by the sounding-box, and by the vibrations of all the strings harmonic with those played.

In the *violin* and *guitar*, each string can give a great number of sounds according to the length of the vibrating part, which is determined by the pressure of the fingers of the left hand while the right hand plays the bow or the strings themselves. In both these instruments the vibrations are communicated to the upper face of the sounding-box by means of the bridge over which the strings pass. These vibrations are communicated from the upper to the lower face of the box, either by the sides or by an intermediate piece called the *sound-post*. The air in the interior is set in vibration by both faces, and the strengthening of the sound is produced by all these simultaneous vibrations. The value of the instrument consists in the perfection with which all possible sounds are intensified, which depends essentially on the quality of the wood and the relative arrangement of the parts.

Instruments of the class of the violin are very difficult to play, and require a delicate ear ; but in the hands of skilful artists they produce marvellous effects. They are the very soul of an orchestra, and the most beautiful pieces of music have been composed for them.

The *Æolian harp* consists of a sounding-box three feet in length by five in width and three in height. On this are two bridges, over which are stretched, though not too tightly, six or eight violin strings tuned in unison. The instrument is placed towards evening in a window opened at the bottom, so as just to admit it. The strings are set in vibration by gentle motion of the air; they divide into different numbers of equal parts, giving rise to various harmonics which combine to produce a most pleasing sound.

A similar phenomenon is often met with in *telegraph wires* ; during strong winds the telegraph posts act in this case as sounding-boards.

199. **Longitudinal vibrations of strings and rods.**—When a violin bow is passed over the string of the sonometer at a very acute angle, an unpleasant but powerful tone is heard. If the tension of the string be altered, there is no change in the note. If the string be touched in the middle, it yields the octave when the bow is passed over it. These tones are produced by longitudinal vibrations ; their pitch varies inversely as the length of the string, but is independent of the thickness and tension. In like manner, if a glass tube be grasped in the middle, and rubbed lengthwise

with a wet cloth, a penetrating but not unpleasant tone is produced. If grasped at a quarter of its length, and if the shorter part be made to vibrate, the octave of the former tone is obtained.

Marloyè's harp (fig. 200) is an arrangement which illustrates the sounds produced by the longitudinal vibration of rods. It consists of a series of deal rods of different lengths and thicknesses. They are sounded by rubbing the rods lengthwise with resined fingers. A series of notes of varying pitch is thus produced, which in the hands of a skilful artist is far from unpleasing.

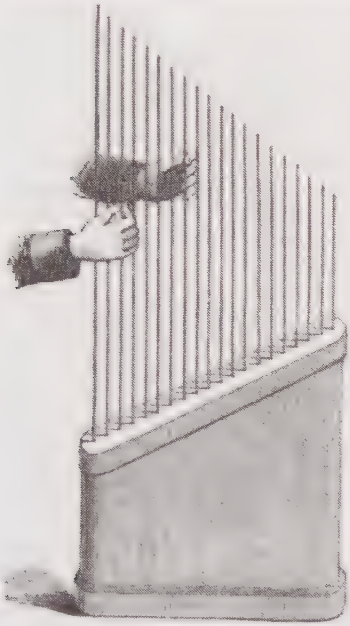


Fig. 200.

Fig. 201.

Another instrument of this kind is the *harmonicon*. This consists of plates of glass or of brass, of the same breadth and thickness, but of different lengths (fig. 201). They are fastened on two narrow ribbons, stretched in a converging direction on a suitable support, which is sometimes provided with a sound-board. If any of these plates is struck with a small padded wooden hammer, it gives a tone which is higher the shorter the plate.

An instrument of this kind, with steel plates, is played by Papageno in the 'Zauberflöte.' If the strips of glass are replaced by strips of wood laid upon plaits of straw, we have what is known as the *straw fiddle*.

A similar arrangement of a number of pieces of flint of suitable sizes gives beautiful sounds when struck (184), and is known as the *geological piano.*

The *tuning-fork*, the *triangle*, and *musical boxes* are examples of the transverse vibration of rods. In musical boxes small plates of steel of different dimensions are fixed on a rod like the teeth of a comb. A cylinder whose axis is parallel to this rod, and whose surface is studded with steel teeth arranged in a certain order, is placed near the plates. By means of a clockwork motion the cylinder rotates, and the teeth, striking the steel plates, set them in vibration, producing a tune, which depends on the arrangement of the teeth on the cylinder.

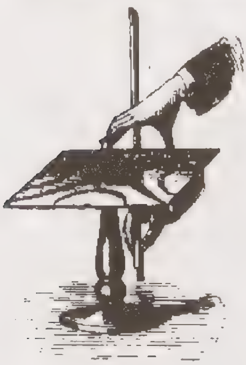


Fig. 202.

200. **Chladni's figures.**—The vibration of plates may be well illustrated by what are known as *Chladni's figures.* A metal plate is clamped, as represented in fig. 202, and a violin bow is passed smartly along the edge. In this way higher or lower notes are produced corresponding to different periods of vibration of the plate. These vibrations are made apparent if the plate has been previously strewn with sand ; the plate divides itself into vibratory segments, in which the vibration is at a maximum, separated from each other by nodal lines or places of no vibration. The sand dances off these segments and gradually settles on the lines, and thus forms beautiful and characteristic figures. These vibrating parts are of less extent, and therefore the nodal lines more numerous, the higher the tones. Their arrangement, and therewith the nature of the tones, depends, with one and the same plate, on the manner in which it is sounded by the bow, and also on the way in which it is damped. If a particular point of the plate is damped, a nodal line is produced passing through the given point, and, at the same time that a special system of nodal lines is formed, a new note results from the vibration. Figures 203 to 206 represent the figures produced when the plate is stroked with a bow in the part denoted by the letter *b*, while at the same time the plate is damped by the finger being held at *a*. If the plate is damped elsewhere than in the centre, other and more complicated figures are produced.

When bells vibrate they divide into an even number of segments separated by nodal lines. This is very easily illustrated by

Fig. 203

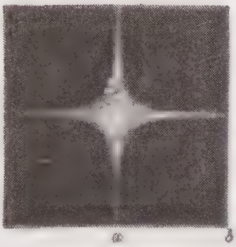
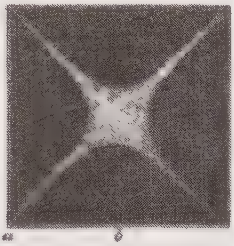


Fig. 204.



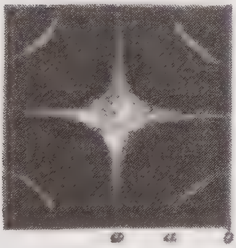


Fig. 205.

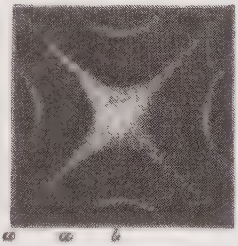


Fig. 206.

means of a glass goblet, A (fig. 207), containing water or, still better, alcohol, which is excited by a bow ; the ventral segments are seen in the ripples on the surface, *a b*, and with a strong vibration by minute droplets thrown in all directions, which roll on the surface of the agitated liquid without mixing with it. The lines *g h* and *c d* represent the nodal lines.

The position of the nodes in a vibrating bell may also be seen in the experiment in fig. 178 : by applying the ball, *d*, to various parts of the rim, certain positions, *c*, *b*, will be found where it is not thrown off ; these are the nodes.

Fig. 207.

CHAPTER IV

ORGAN-PIPES AND WIND INSTRUMENTS

201. **Production of sound in pipes.**—Sound-pipes are hollow pipes or tubes in which sounds are produced by making the enclosed column of air vibrate. In the cases hitherto considered the sound results from the vibration of solid bodies, and the air only serves as a vehicle for transmitting them. In wind instruments, on the contrary, when the sides of the tube are of adequate thickness, the enclosed column of air is the sounding body, and the pitch and intensity depend on the dimensions of this column. In fact, the substance of the tubes is without influence on the primary tone; with equal dimensions it is the same whether the tubes are of glass, of wood, or of metal. It may even be of such an inelastic metal as lead. These different materials do no more than give rise to different harmonics, and impart a different timbre (185) to the compound tone produced.

If tubes were simply blown into, there could be no sound; there would merely be a continuous progressive motion of the air. To produce a sound a rapid succession of condensations and rarefactions must by some means or other be set up, which are then transmitted to the whole column of air in the tube. Hence the necessity of having a *mouthpiece*—that is, the end by which air enters—so shaped that the air may be made to enter in an intermittent, and not a continuous, manner. From the arrangement made use of to set the enclosed air in vibration, wind instruments are divided into *mouth* instruments and *reed* instruments.

202. **Mouth instruments.**—In mouth instruments all parts of the mouthpiece are fixed. The pipes are either of wood or of metal, rectangular or cylindrical, and are always long as compared with the diameter. Fig. 208 represents a wooden rectangular organ-pipe; fig. 209 gives a longitudinal section, by which the internal details are seen. The lower part, P, by which air enters, is called the *foot*; the air emerges through a narrow slit, *i*, close

to which, in front of the pipe, is a transverse aperture called the *mouth* ; *a* and *b* are the *lips*, the upper one of which is bevelled.

The current of air, arriving by the narrow slit, strikes against the upper lip, is compressed, and, by its elasticity, reacts upon the current, and stops it. This, however, only lasts for an instant, for as the air escapes at *ab*, the current from the foot continues, and so on for the whole time.

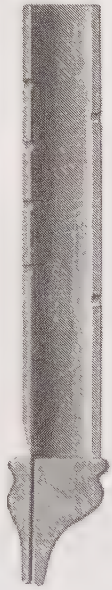



Fig. 208. Fig. 209. Fig. 210. Fig. 211. Fig. 212.

In this way pulsations are produced, which, transmitted to the air in the pipe, make it vibrate, and a sound is the result. In order that a pure note may be produced, there must be a certain relation between the form of the lips and the magnitude of the mouthpiece ; the tube also ought to have a considerable length in comparison with its diameter. The number of vibrations depends in general on the dimensions of the pipe and the velocity of the current of air.

The mouthpiece we have described is used in organs Fig. 210

represents another modification much in use in organ-playing, and fig. 211 gives a longitudinal section. The letters indicate the same parts as in fig. 209. Fig. 212 shows the mouthpiece of a flageolet and whistle. In the German flute the mouthpiece consists of a small lateral round aperture in the pipe. By means of his lips the player causes the current of air to graze against the edge of this aperture.

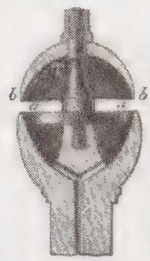


Fig. 213.

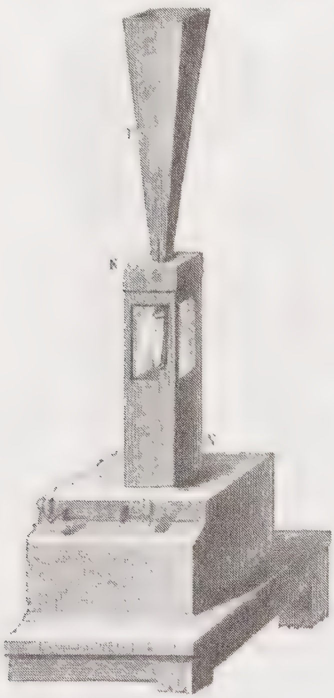


Fig. 214.

Fig. 215.

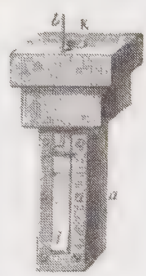


Fig. 216.

A *steam whistle* (fig. 213) is really only a closed organ pipe with a mouthpiece formed of a circular slit, *a a*, above which is placed the sharp edge, *b b*, of the bell, T.

203. **Reed instruments.**—In reed instruments the air is set in vibration by means of elastic tongues or plates, which are called *reeds*, and which are divided into free reeds and beating reeds.

Beating reed.—This consists of a piece of wood or metal, *a* (fig. 215), which is grooved like a spoon. It is fixed to a kind of stopper, K, perforated by a hole, which connects the cavity with a long pipe, T. The groove is covered by a brass plate, *l*, which is called the *tongue*. In its ordinary position it is slightly away from the edges of the groove, but, being very flexible, readily approaches and closes it. Lastly, a curved wire, *br*, presses against the tongue, and can be moved up and down. The vibrating part of the tongue can thereby be shortened or lengthened at will, and the number of vibrations thus regulated. By means of this wire reed pipes are tuned.

The reed is fitted to the top of a rectangular pipe KN, called the *wind-channel*. This is closed everywhere, except at the bottom, where it can be fitted on a bellows. In models of reed pipes used in illustrating lectures, the sides of the upper part of the tube are made of glass, so as to show the construction of the reed. This arrangement is represented in fig. 214.

When air arrives in the wind-channel, it first passes between the tongue and the groove, and escapes by the pipe T; but, as the velocity increases, the tongue strikes against the edge of the groove, and, closing it completely, the current is stopped. But, in virtue of its elasticity, the tongue reverts to its original position, and thus, by a series of alternate openings and closings, the same series of pulsations is produced as in mouth instruments; hence is produced a note the pitch of which depends upon the frequency of the reed.

Free reed.—This is a kind of reed so called because the tongue, instead of striking against the edges of the groove, like the reed described above, grazes them so as to oscillate backwards and forwards (fig. 216). The tongue of the reed fits into and almost

Fig. 217.

closes a longitudinal slit cut in the metal front of a small wooden box, *a* (fig. 216). The tongue oscillates in such a way as to allow air to pass, and closes the slit each time it grazes its edges. In this case also a wire, *b*, regulates the length of the vibrating part of the tongue.

A reed can be very simply made from a piece of straw. About an inch from a knot an incision is made at *r* (fig. 217), with a

sharp penknife, about a quarter as deep as the diameter of the straw ; and then, by laying the knife flat, the straw is slit as far as the knot ; the strip, *rr*, thus produced forms a reed joined with the pipe, *sr*. The note of this pipe depends on the length of the tube *sr*, and is higher the shorter the tube is made. In order to sound the pipe, the whole length of the reed is placed in the mouth, and the lips firmly closed.

204. **Bellows.**—In acoustics a *bellows* is an apparatus by which wind instruments, such as the siren and organ-pipes, are worked.

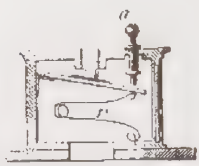


Fig. 219.

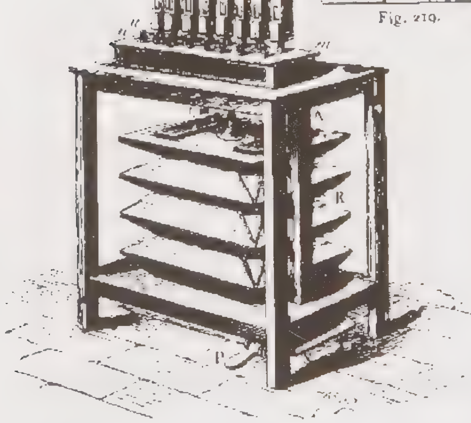


Fig. 218.

Between the four legs of a table there is a pair of bellows, S (fig. 218), which is worked by means of a pedal, P. R is a reservoir of flexible leather, in which is stored the air forced in by the bellows. If this reservoir is pressed by means of weights on a rod, T, moved by the hand, the air is driven through a pipe, A, into a *wind-chest*, *mn*, fixed on the table. In this chest there are small holes closed

by leather valves, *s* (fig. 219). These can be opened by pressing on keys, *a*, in front of the box. Below the valve is a spring, *r*, which raises the valve when the key is not depressed. The sound pipe is placed in one of these holes.

205. **Nodes and loops.**—Experiment shows that when a pipe is sounded, the air particles in it are set in longitudinal vibration, and stationary waves are formed. In the case of an open pipe sounding its lowest or fundamental note, the amplitude of the vibrations is least at the middle and a maximum at the two ends. The middle point is called a node, and the ends are the middle points of loops or ventral segments, the length of the pipe being half the length of a wave. The middle point of a ventral segment is called an *antinode*. If the pipe is sounding a harmonic of the fundamental, there may be several ventral segments separated by nodes, but the ends are always the middle points of ventral segments. In the case of a pipe closed at one end, a stopped pipe, the closed end is always a node, and the open end an antinode.


Fig. 220.

When an aperture is opened in the side of a sounding pipe, the sound does not change if the aperture is made in the middle of a loop; but if it corresponds to a node, the sound is altered, for this node then becomes a loop. This property is used in wind instruments like the flute, or the clarionet, along which holes are made which can be closed by the fingers, or by the aid of keys.

There are many experiments by which the existence of nodes and loops in a sounding pipe may be shown.

If a fine membrane is stretched over a pasteboard ring, and has sprinkled on it some fine sand, it can be gradually let down a tube, as shown in fig. 220. Now, suppose the tube to be producing a musical note. As the membrane descends, it will be set in vibration by the vibrating air. But when it reaches a node it will cease to vibrate, for there the air is at rest. Consequently, the grains of sand, too, will be at rest, and

their quiescence will indicate the position of the node. On the other hand, when the membrane reaches the middle of a loop—that is, a point where the amplitude of the vibrations of the air attains a maximum—it will be violently agitated, as will be shown by the agitation of the grains of sand. And thus the positions of the loops can be rendered manifest.

The formation of nodes and loops in a sounding pipe may also be shown by what are known as Kundt's *dust figures.* A simple modification of the experiment by Mayer is the following. A portion of a child's wooden whistle (fig. 221) is cut off just behind

Fig. 221.

the first finger-hole, and cemented into a glass tube about three times its length. This tube is closed at the end with a cork, and contains a quantity of powdered silica, or of very finely sifted sand. When the pipe is sounded by blowing into it, the dust is set in vibration, and arranges itself in small patches in a certain definite order, accumulating at the nodes. The distance between two neighbouring heaps is half the wave length in air corresponding to the note of the whistle.

206. **Vibration of air in pipes.**—The vibrations of air in pipes present two cases according as the pipes are *open* or *stopped.*

Stopped pipes.—When, having placed a stopped pipe on the bellows, air is slowly passed, the fundamental note of the pipe is produced. If, then, we denote by 1 the corresponding number of vibrations, when the current of air is forced we suddenly get the sound corresponding to 3 ; and if the wind be still more forced we have successively the sounds 5, 7, etc. : that is to say, sounds which by their pitch correspond to vibrations, 3, 5, 7, etc. times as numerous as those of the fundamental sound. Hence when the air is forced stopped pipes give successively notes whose frequencies are represented by the series of odd numbers.

With pipes of different lengths, the numbers of vibrations corresponding to the fundamental note are inversely as the lengths ; that is to say, a pipe which is half as long as another will yield the octave of the first note.

Open pipes.—The fundamental note being still represented by unity, the harmonics obtained by forcing the wind are successively represented by 2, 3, 4, 5, 6, etc., that is, by the natural series of numbers.

The fundamental note of an open pipe is always an octave higher than the fundamental note of a closed pipe of the same length.

This may be shown by the apparatus represented in fig. 222, which consists of an open pipe, provided with a sliding diaphragm of the same cross-section as that of the pipe. When the diaphragm is pushed in, the whole length of the pipe is open, but half of it is closed when the diaphragm is as represented in the figure. In the latter case we have the fundamental note of a closed pipe of length V N. When the diaphragm is inserted we have the fundamental note of an open pipe of twice the length, V V′, and in both cases the sound is the same.

207. **Pitch pipe.**—Instead of using bellows and organ pipes of various lengths, these laws may be conveniently demonstrated by means of a *pitch* pipe (fig. 223), which is a small sound-pipe with a movable graduated stopper. If, having closed the pipe at its full length, we blow into it, we get the fundamental note of the stopped pipe, say c; if now we blow into it more strongly, we get the note g' (192), which is the fifth of the higher octave of c; and more strongly still, the note e'', which is the major third of its second octave; and so on for the others.

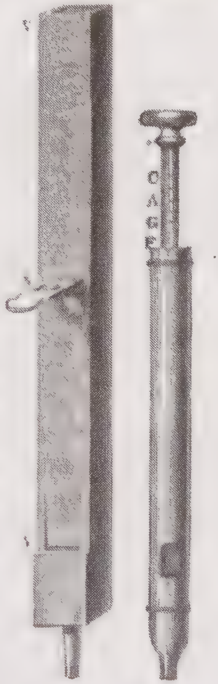


Fig. 222. Fig. 223.

In like manner, having just closed the pipe, if we push in the stopper until its length is one half and sound it, we get the higher octave of the fundamental note; by making it $\frac{1}{3}$ its original length we get the fifth of the higher octave of c; and so for any other aliquot part.

By removing the stopper altogether we have an open pipe, and the note c' which it yields is the octave of the stopped one, and

this, sounded by increasingly powerful currents of air, gives the following series of notes, c'', g'', c''', e''' (192), and so forth.

208. **Wind instruments.**—Wind instruments are straight or curved tubes, the air in which is set in vibration by suitable means. They are divided into mouth instruments and reed instruments; in some, such as the organ, the notes are *fixed*, and require a separate pipe for each note; in others the notes are *variable*, and are produced by only one tube; the flute, horn, etc., are of this class.

The Pan's pipes, the flageolet, and the German flute are mouth instruments. The principal reed instruments are the clarinet, the oboe, and the bassoon.

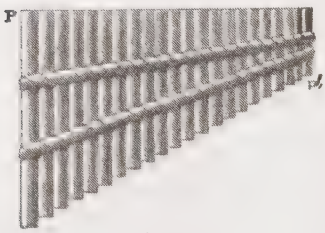


Fig. 224.

The *Pan's pipes* (fig. 224) consist of tubes of different sizes corresponding to the different notes of the gamut.

In the *organ* the pipes are of various kinds—namely, mouth pipes, open and stopped, and reed pipes with apertures of various shapes. The air is furnished by means of bellows, from which it passes into the wind chest, and thence into any pipe which is desired; this is effected by means of valves which are opened by depressing keys like those of the piano. In the larger organs there are several rows of key-boards arranged at different heights.

Fig. 225.

In the *flute* the mouthpiece consists of a simple lateral circular aperture; the current of air is directed by means of the lips so that it grazes the edge of the aperture. The holes at different distances are closed either by the fingers or by keys; when one of the holes is opened, an antinode (205) is produced in the corresponding layer of air, which modifies the distribution of nodes and loops in the interior, and thus alters the note. The *whistling* of a key is similarly produced.

Mouth instruments.—In the trumpet, the horn, the trombone, cornet-à-piston, and ophicleide the lips form the reed, and vibrate

in the mouthpiece (fig. 225), which terminates in a smaller tube by which it can be affixed to the instrument. In the *horn*, different notes are produced by altering the tension of the lips. In the *trombone*, one part of the tube slides within the other, and the performer can alter at will the length of the tube, and thus produce higher or lower notes. In the *cornet-à-piston*, the tube forms several convolutions ; pistons placed at different distances can, when played, cut off communication with other parts of the tube, and thus alter the length of the vibrating column of air.

209. **The human voice.**—If we bevel off the ends of a piece of wooden tubing, so that two summits are left, and if now two pieces of thin vulcanised india rubber or leather be stretched and tied between them so as to leave a narrow slit, we have a sort of membranous reed pipe (fig. 226). For if we blow into the tube we

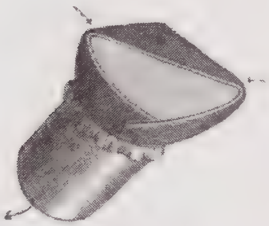


Fig. 226.

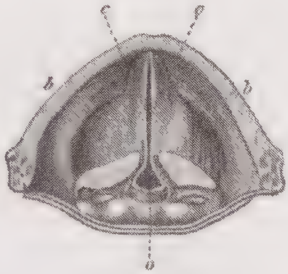


Fig. 227.

get a note which is higher the tighter the lips are stretched ; and the vibrations of the lips which form the slit can be distinctly seen.

This, which is in effect an artificial larynx, well illustrates the manner in which the sound of the human voice is produced.

The *trachea* or *windpipe* is a tube which terminates at one end in the lungs, and at the other in the *larynx*, which is the true organ of vocal sound. Fig. 227 represents a horizontal section of this organ. It consists of a number of cartilaginous structures, *b b*, which are connected by various muscles, by which great variety and control in the motions are attainable. These muscles are connected with, and move, two elastic membranes or bands with broad bases fixed to the larynx, and with sharp edges *c c* ; these are called the *vocal cords.* According to the pressure of the muscles these cords are more or less tightly stretched, and the

space between them, the *vocal slit*, is narrower or wider accordingly. In ordinary breathing, air passes through the triangular aperture *o*; but when this is contracted in singing, the vocal cords are stretched, and put in vibration by the current of air, and produce tones which are higher the more tightly the cords are stretched and the narrower is the vocal slit. These vibrations are communicated to the air in the larynx, and in the cavity of the mouth. The changes can be effected with surprising rapidity, so that in this respect the human voice far surpasses anything that can be made artificially.

The notes produced by men are deeper than those of women or boys, because in them the larynx is longer and the vocal cords larger and thicker; hence, though equally elastic, they vibrate less swiftly. The vocal cords are 18 millimetres long in men, and 12 millimetres long in women. Chest notes are due to the fact that the whole membrane vibrates, while the falsetto is produced by a vibration of the extreme edges only. The ordinary compass of the individual voice is within two octaves, though this is exceeded by some celebrated singers.

The essential sonorous part of the human voice depends upon the *vowels*. The form and cavity of the mouth can be greatly modified by the extent to which it is opened, by the altered position of the tongue, and so forth. It thus forms a resonator which can be quickly and completely controlled. When the mouth is adjusted so as to produce the broad A, as in *father*, it has then a sort of funnel shape, with the wide part outward; for O, as in *more*, the effect is like that of a bottle with a wide neck; and for U, as in *poor*, it is that of a similar bottle with a narrow neck. For the other vowels, such as A, E, and I, the effect is as if the bottle were prolonged by a tube, formed by contracting the tongue against the palate.

The sounds by which the consonants are produced are much less strong than the vowel sounds. They are thus inaudible at distances at which the vowel sounds can be distinctly heard. Hence, in speaking with people hard of hearing, it is by no means necessary to speak louder, but it is sufficient to accentuate the consonants. Indeed, distinctness of speech does not depend on loud screaming, but is produced by careful articulation.

210. **The Ear.**—The organ of hearing in man consists of several structures; the outer ear, A (fig. 228), by which the sound is collected and transmitted through the *auditory passage*, B, to the *drum*

or *tympanum*, C. This is a delicate, tightly stretched membrane or skin separating the outer ear from the middle ear or *tympanic cavity*. This is a cavity in the temporal bone in which are several small bones whose dimensions are considerably exaggerated in the figure. One of these, the *hammer*, M, is attached at one end to the tympanic membrane, and at the other is jointed to the *anvil*, E; the latter is connected by means of a small lens-shaped bone, L, to the *stirrup bone*, K (fig. 229), and therewith to the *oval window*, an aperture closed by a fine membrane which separates the tympanic cavity from the *labyrinth*. The tympanic cavity is also connected

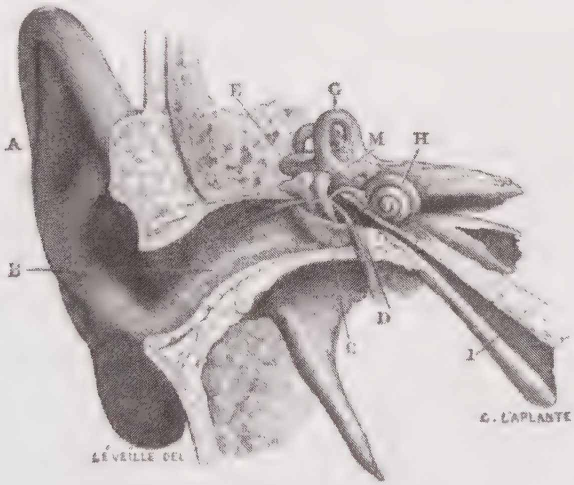


Fig. 228.

by the *Eustachian tube* with the cavity of the mouth, so that the air in it is always under the same pressure.

The labyrinth is a complicated structure filled with fluid; it is entirely of bone, with the exception of the oval window already mentioned and the *round window*. The labyrinth consists of three parts: the *vestibule*, which is closed by the oval window; the three semicircular canals, G; and the spiral-shaped *cochlea* or snail shell, H, fig. 228, shown in section in fig. 230. This is divided throughout its entire length by a diaphragm partly of bony projection and partly of membrane; the upper part of this division is

connected with the vestibule, and therefore with the oval window, while the lower part is connected with the round window. In the labyrinthine fluid of this part the termination of the auditory nerve is spread, the other end leading to the brain.

The drum of the ear may be injured without the sense of hearing being lost, but if the labyrinth is injured, or if the auditory nerve ceases to act, deafness is produced.

The membranous part of this diaphragm is lined with about 3,000 extremely minute fibres, which are the terminations of the acoustic nerve. Each of these, which are called *Corti's fibres*, seems to be tuned for a particular note as if it were a small

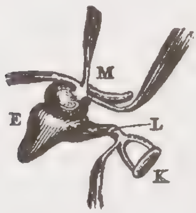


Fig. 229.

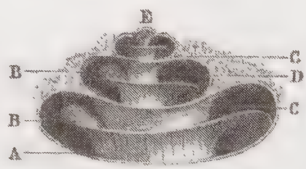


Fig. 230.

resonator (194). Thus when the vibrations of any particular note reach these fibres, through the intervention of the stirrup bone and the fluid of the labyrinth, one fibre or set of fibres only vibrates in unison with this note, and is deaf to all others. Hence each simple note causes one fibre only to vibrate, while compound notes cause several ; just as when we sing near a piano with the dampers raised from the strings, only those strings are set in vibration which correspond to the fundamental notes sung and their harmonics. Thus, however complex external sounds may be, these microscopic fibres can analyse them and reveal the constituents of which they are formed.

BOOK V

ON HEAT

CHAPTER I

GENERAL EFFECT OF HEAT. THERMOMETERS

211. **Heat. Hypothesis as to its nature.**—The sensations of heat and cold are familiar to all of us. In ordinary language the term *heat* is used not only to express a particular sensation, but also to describe that particular state or condition of matter which produces this sensation. Besides producing this sensation, heat acts variously upon bodies ; it melts ice, boils water, makes metals red-hot, decomposes chemical compounds, and so forth.

On the modern view the heat of a body is caused by an oscillating or vibratory motion of its material particles, and the hottest bodies are those in which the vibrations have the greatest frequency and the greatest amplitude. Hence, on this view, heat is not a *substance*, but a *condition of matter*, and a condition which can be transferred from one body to another. It is also assumed that there is an imponderable elastic ether, which pervades all bodies, the densest or the most transparent solids or liquids, the most attenuated gases as well as the stellar spaces, and which is capable of transmitting a vibratory motion with great velocity. It is by the rapid vibratory motion of this ether that heat is transferred from one body or place to another, just as sound is transmitted by a vibratory motion of atmospheric air.

This hypothesis is now admitted as affording a better explanation of the phenomena of heat than any other theory, and it reveals an intimate connection between heat, light, and electricity. In

accordance with it, heat is a *form of energy* ; and it can be shown that heat may be converted into the energy of motion, and, conversely, that motion may be converted into heat.

Although the undulatory theory of heat is the one which best explains and accounts for the greatest number of facts, yet it may be sometimes convenient to use language which is based on older hypotheses. Thus, in speaking of a body becoming heated or cooled, we say that it gains or loses heat ; in reality, the vibratory motion of the particles is increased or diminished.

In what follows, however, the phenomena of heat will, as far as possible, be considered independently of any hypothesis.

212. **General effects of heat.**—The general effects of heat upon bodies are to increase the velocity of the vibratory motion of their molecules, and accordingly to lessen molecular attraction. Under its influence, therefore, bodies tend to *expand*—that is, to assume a greater volume.

All bodies expand by the action of heat. As a general rule, gases are the most expansible, then liquids, and lastly solids. The expansion of bodies by heat is thus a new general property to be added to those already studied (8).

The action of heat upon bodies is not merely to expand them ; when gradually heated, bodies first lose their solidity and become somewhat softer ; then, as the heat still increases, the forces holding the particles change their character, and the bodies liquefy. Wax, resin, sulphur, thus pass readily from the solid to the liquid state ; heat, therefore, produces in solids a change of state of aggregation. But in liquids it also produces a similar change. When liquids are heated they first expand ; heated still more, their molecular attraction is overcome, and the liquids are changed into aëriform fluids called vapours.

If, instead of becoming accumulated in bodies, heat is given out—that is, if bodies are cooled instead of being heated—the opposite phenomena are produced ; the molecules come nearer each other, the volume of the pores diminishes, and with it that of the body ; which is expressed by saying that the body *contracts*. By cooling, vapours, losing their elastic force, revert to the liquid state ; and liquids themselves, by the same process, gradually return to the solid state. Thus water changes into ice, and mercury becomes as hard as lead.

Hence as heat increases in, or is lost by, bodies, two physical effects may be produced : 1. Changes in volume, consisting in

expansions and contractions. 2. Changes of condition—that is, the change of solids into liquids, of liquids into vapours, and conversely. We shall first discuss the expansion of bodies, and afterwards their changes of state.

213. **Expansion.**—All bodies are expanded by heat, but to very different extents. Gases are the most expansible of substances, solids the least.

In solids, which have definite figures, we can either consider the expansion in one dimension, or the *linear* expansion ; in two dimensions, the *superficial* expansion ; or in three dimensions, the *cubical* expansion or the expansion of volume, although one of these never

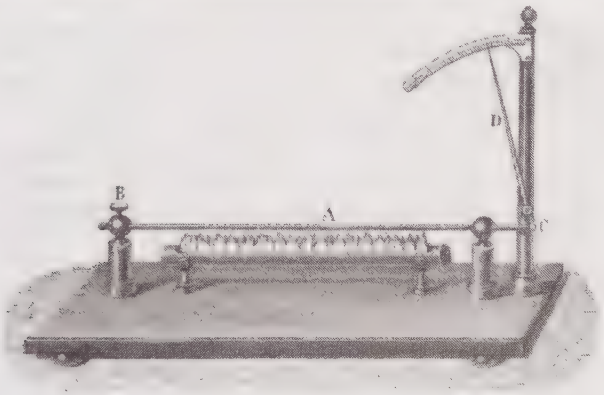


Fig. 231.

takes places without the others. As liquids and gases have no definite shapes, we can only consider the alterations of volume which they undergo.

To show the linear expansion of solids, the apparatus represented in fig. 231 may be used. A metal rod, A, is fixed at one end by a screw, B, while the other end presses against the short arm, C, of a lever, D, the end of the long arm of which moves over a scale. Below the rod, A, there is a sort of cylindrical trough in which spirit is burned. The needle, D, is at first at the zero point, but, as the rod becomes heated, the needle moves along the scale, which shows that the short arm, C, of the lever is slightly displaced, pushed by the rod, A, as it expands.

It will be observed that, if rods of different metals are used, the index will be moved to different extents, showing that their expansibility differs. Thus it will be found that brass is more expansible than iron or steel.

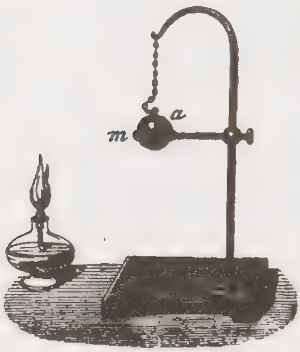


Fig. 232.

The cubical expansion of solids may be shown by means of a *Gravesande's* ring. It consists of a brass ball, *a* (fig. 232), which at the ordinary temperature passes freely through a ring, *m*, of almost the same diameter. But when the ball has been heated, it expands and no longer passes through the ring. It does so, however, on reverting to its original temperature.

This experiment may be slightly varied by using a truncated copper cone, A, and a copper ring, C (fig. 233); at the ordinary temperature the ring stands at the mark *a*. When the cone alone is heated, it will be found that the ring stands at the mark a'; while if the ring and not the cone is heated it stands at a''; if both are simultaneously heated at the same temperature, it stands at the same mark as at first.

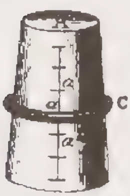


Fig. 233.

The expansibility of liquids and gases, which is far greater than that of solids, is easily shown. For a liquid, a glass tube with a bulb at one end may be used (fig. 234), which is filled with some liquid, coloured alcohol for instance. When the bulb is gently heated, by placing it in tepid water, for example, the column of liquid is seen to rise considerably in the tube; thus from *a* to *b*, and the expansion thus observed is far greater than in the case of solids.

The same apparatus may be used for showing the expansion of gases. The bulb being filled with air, a small thread of mercury is introduced into the capillary tube to serve as index (fig. 235). When the globe is heated in the slightest degree, even by approaching the hand, the expansion is so great that the index is driven to the end of the tube, and is finally expelled. It is thus seen that gases are highly expansible.

In these different experiments the bodies contract on cooling, and when they have attained their former temperature they resume their original volume. Certain metals, however, especially zinc, form an exception to this rule, as do also some kinds of glass.

It will thus be seen that the general effect of heat upon bodies is to expand them. Yet this only applies to bodies which, like the metals, glass, etc., do not absorb moisture. Bodies which absorb moisture, such as wood, paper, clay, undergo a contraction when heated, owing to the heat expelling moisture from their pores. Thus a moist sheet of paper placed before the fire coils up on the heated side. Coopers, in order to curve the staves of barrels, heat them on one side, by lighting a fire on the inside of the barrel when the staves are placed close together. The part turned towards the fire contracts in drying, and becomes concave on the side exposed to the direct action of heat.

Fig. 234. Fig. 235.

MEASUREMENT OF TEMPERATURES. THERMOMETRY

214. **Temperature.**—The *temperature* or *hotness* of a body may be defined as being the greater or less tendency which it has to impart sensible heat to other bodies. The temperature of any particular body is varied by adding to or withdrawing from the body a certain amount of sensible heat. The temperature of a body must not be confounded with the *quantity* of heat it possesses; a body may have a high temperature and yet have a very small quantity of heat, and conversely, with a low temperature may possess a large amount of heat. If a cup of water be taken from a bucketful, both will have the same temperature, yet the quantities of heat they possess will be very different. The subject of the quantity of heat will be afterwards more fully explained in the chapter on SPECIFIC HEAT.

215. **Thermometers.**—*Thermometers* are instruments for measuring temperature. Owing to the imperfections of our senses we are unable accurately to measure the temperature of a body by the

sensation of heat or cold which it produces in us, and hence recourse must be had to the physical effects of heat upon bodies. The most accurate and the most convenient are the effects of expansion. Solids, having but little expansibility, can only be used to examine large intervals of temperature ; gases, on the other hand, are very expansible, and only serve to measure small ones. They are, moreover, affected by changes of atmospheric pressure. For these reasons, liquids are best suited for the construction of ordinary thermometers. Mercury and alcohol are in practice the only ones used—the former because its expansion is regular, and it only boils at a high temperature ; and the latter because it does not solidify until a very low temperature is reached.

Fig. 236.

Fig. 237.

The mercurial thermometer is the one most extensively used. It consists of a capillary glass tube, at the end of which is blown the *bulb*, a cylindrical or spherical reservoir (fig. 237). Both the bulb and a part of the stem are filled with mercury, and the expansion is measured by a scale graduated either on the stem itself (fig. 240), or on a frame to which it is attached (fig. 243).

The filling of the tube with mercury may be effected by fusing to the tube a small funnel, as shown in fig. 236. In this is placed a small quantity of mercury, and the bulb is then gently heated by a spirit lamp. The expanded air partially escapes by the funnel, and, on cooling, the air which remains contracts, and a portion of the mercury passes into the bulb. The bulb is then again warmed, and allowed to cool, a fresh quantity of mercury enters, and so on, until the bulb and part of the tube are full of mercury. The mercury is then heated to boiling ; the mercurial vapour in escaping carries with it the air and moisture which remain in the tube. The tube, being thus full of the expanded mercury and of mercurial vapour, is hermetically sealed at the end. When the thermometer is cold the mercury ought to fill the bulb and a portion of the stem.

216. **Graduation of the thermometer.**—The thermometer having been filled, as has just been described, the mercury rises or sinks in the stem whenever the temperature rises or sinks, and these variations furnish a means of measuring temperatures. For the purpose of measuring these variations a graduated scale must be constructed along the stem. In graduating the scale two points must be taken, which represent definite fixed temperatures and which can always be easily produced.

Fig. 238.

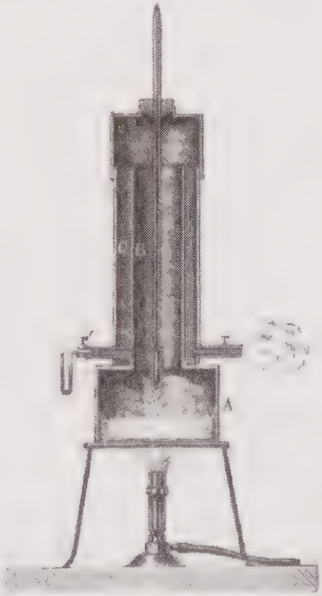


Fig. 239.

Experiment has shown that ice always melts at the same temperature to whatever source of heat it is exposed (249), and that distilled water under the same pressure, and in a vessel of the same kind, always boils at the same temperature. Consequently, for the first fixed point the temperature of melting ice has been taken; and, for the second fixed point, the temperature of boiling water in a metal vessel under the standard atmospheric pressure of 30 inches (128).

This interval of temperature—that is, the range from the melting point of ice to the boiling point of water—is taken as the unit for comparing temperatures ; just as a certain length, a foot or a yard for instance, is used as a basis for comparing lengths.

To obtain the lower fixed point, snow or pounded ice is placed in a vessel (fig. 238). The bulb and a part of the stem of the thermometer are immersed in this for about a quarter of an hour ; the mercury sinks, and the level at which it finally rests is marked by a scratching diamond.

The second fixed point is determined by means of the apparatus represented in fig. 239. It consists of a metal vessel containing distilled water which can be boiled by a Bunsen burner placed underneath. From it rises a tube, B, open at the top and surrounded by an outer cylinder, C, through a cork in the top of which the thermometer passes. The outer tube serves as a steam-jacket for the inner. The steam rising in the inner tube descends between it and the outer and escapes by the lateral aperture r. The small tube r' on the other side communicates with the inside of the vessel, and has attached to it a glass siphon manometer containing water or mercury. This serves to inform the observer whether the pressure of the steam is the same as that of the outside atmosphere. The steam is at the same temperature as the water from which it is liberated, and, when the mercury is stationary, a second mark is scratched upon the stem.

217. **Construction of the scale.**—Just as the foot-rule, which is adopted as the unit of comparison for length, is divided into a number of equal divisions called inches, for the purpose of having a smaller unit of comparison, so likewise the unit of temperatures, the range from the freezing to the boiling point of water, must be divided into a number of parts of equal capacity called *degrees*. There are three methods by which this is done. On the Continent, and more especially in France, this space is divided into 100 parts, zero corresponding to the melting point of ice, and 100 degrees to the boiling point of water, and this division is called the *Centigrade* or *Celsius* scale; the latter being the name of the inventor. The Centigrade thermometer is almost exclusively adopted in foreign scientific works, and, as its use is gradually extending in this country, it has been and will be adopted in this book.

The degrees are designated by a small cipher placed a little above on the right of the number which marks the temperature. The graduation is continued above 100° and below zero,

and to indicate temperatures below zero the minus sign is placed before them. Thus $-15°$ signifies 15 degrees below zero. In accurate thermometers the scale is marked on the stem itself (fig. 240). It cannot be displaced, and its length remains fixed, since glass has very little expansibility. This marking is effected by coating the stem with a thin layer of wax, and then marking the divisions of the scale, as well as the corresponding numbers, with a steel point. The thermometer is then exposed for about ten minutes to the vapours of a substance called *hydrofluoric acid*, which bites into the glass where the wax has been removed. The rest of the wax is then dissolved off by means of turpentine, and the stem is found to be permanently etched.


Fig. 240.

Scales are also constructed on plates of ivory, wood, or metal, against which the stem is placed. Fig. 243 represents this arrangement.

Besides the *Centigrade* scale, two others are frequently used—*Fahrenheit's scale* and *Réaumur's scale.*

In Réaumur's scale, which is used in Russia and in North Germany, the distance between the fixed points is divided into 80 degrees instead of into 100. That is to say, 80 degrees Réaumur are equal to 100 degrees Centigrade; one degree Réaumur is equal to $\frac{100}{80}$ or $\frac{5}{4}$ of a degree Centigrade, and one degree Centigrade equals $\frac{80}{100}$ or $\frac{4}{5}$ degree Réaumur. Consequently to convert any number of Réaumur degrees into Centigrade degrees (20 for example), it is merely necessary to multiply them by $\frac{5}{4}$ (which gives 25). Similarly, Centigrade degrees are converted into Réaumur's by multiplying them by $\frac{4}{5}$.

The thermometer scale invented by Fahrenheit in 1714 is still much used in England, and also in Holland and North America. The higher point is, like that of the other scales, the temperature of boiling water, but the null-point or zero is the temperature obtained by mixing equal weights of sal-ammoniac and snow, and the interval between the two points is divided into 212 degrees. The zero was selected because the temperature was the lowest then known, and was erroneously thought to represent the lowest attainable temperature. When Fahrenheit's thermometer is placed in melting ice it stands at 32 degrees; and, therefore, 100 degrees on the Centigrade scale are equal to 180 degrees on

the Fahrenheit scale, and thus 1 degree Centigrade is equal to $\frac{9}{5}$ degree Fahrenheit, and conversely 1 degree Fahrenheit is equal to $\frac{5}{9}$ of a degree Centigrade.

If it is required to convert a certain number of Fahrenheit degrees (95 for example) into Centigrade degrees, the number 32 must be first subtracted, in order that the degrees may count from the same point of the scale. The remainder in the example is thus 63, and as 1 degree Fahrenheit is equal to $\frac{5}{9}$ of a degree Centigrade, 63 degrees are equal to $63 \times \frac{5}{9}$ or 35 degrees Centigrade.

If F denotes a certain temperature in Fahrenheit's degrees, C the same temperature in Centigrade degrees, and R in Réaumur degrees, we may state any one of these in terms of either of the other two by the formula

$$\frac{F-32}{9}=\frac{C}{5}=\frac{R}{4}.$$

218. **Alcohol thermometer.**—The *alcohol thermometer* differs from the mercury thermometer in being filled with coloured alcohol. But as the expansion of liquids is less regular in proportion as they are near the boiling point, alcohol, which boils at 78° C., expands very irregularly. Hence, alcohol thermometers are usually graduated by placing them in baths at different temperatures together with a standard mercurial thermometer, and marking the corresponding temperatures.

Fig. 241.

The filling is effected by gently heating the bulb so as to expel a certain quantity of air, then inverting it and plunging the open end into coloured alcohol (fig. 241). The air inside contracts on cooling, and the atmospheric pressure raises the alcohol in the tube and in the bulb. When sufficient liquid has been introduced the end of the tube is sealed, air being purposely left in to prevent breaks in the alcohol column.

219. **Limits to the employment of mercury thermometers.**—Of all thermometers in which liquids are used, the one with mercury

is the most useful, because this liquid expands most regularly, and is easily obtained pure, and because its expansion between – 36° and 100° is most nearly *regular*—that is, proportional to the change of temperature. It also has the advantage of having a very low specific heat (276); and a further advantage is that it does not wet glass. But for temperatures below – 36° C. the alcohol thermometer must be used, since mercury solidifies at – 39° C. Mercury thermometers also cannot be used for temperatures above 350°, for this is the boiling point of mercury.

Observations by means of the thermometer. In taking the temperature of a room, the thermometer is usually suspended against the wall: This may, however, give rise to an error of several degrees; for if the wall communicates with the outside, and especially if it has a northern aspect, it will, generally speaking, be colder than the air in the room, and the thermometer will indicate too low a temperature. On the other hand, it may happen that the wall becomes too much heated by the sun's rays, or by chimney flues, and then the thermometer will be too high. The only way to obtain with accuracy the temperature of the air in a room is to suspend the thermometer by a string in the centre at a distance from any object which might raise or lower its temperature. The same remark applies to the determination of the temperature of the atmosphere; the thermometer must be suspended in the open air, in the shade; and not against a wall.

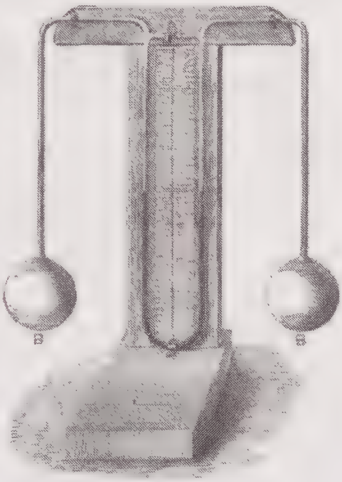


Fig. 242.

220. **Differential thermometer.**—Sir John Leslie constructed a thermometer for showing the difference of temperature of two neighbouring places, from which it has received the name of the *differential thermometer.*

A modified form of it is that devised by Matthiessen (fig. 242), which has the advantage of being available for indicating the

temperature of liquids. It consists of a bent glass tube, each end of which is bent twice, and terminates in a bulb; the bulbs being pendent can be readily immersed in vessels containing liquids. The bend contains some coloured liquid, and in a tube which connects the two limbs is a stopcock, by which the liquid in each limb is easily brought to the same level. The whole is supported by a frame.

When one of the bulbs is at a higher temperature than the other, the liquid in the stem is depressed and rises in the other stem. The instrument is now only used as a *thermoscope*; that is, to indicate a difference of temperature between the two bulbs, and not to measure its amount.

221. **Maximum and minimum thermometers.**—It is necessary, in meteorological observations, to know the highest temperature of the day, and the lowest temperature of the night. Ordinary thermometers could only give these indications by a continuous

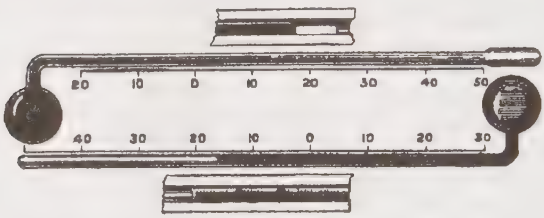


Fig. 243.

observation, which would be impracticable. Several instruments have accordingly been invented for this purpose, the simplest of which is Rutherford's. On a rectangular piece of wood two thermometers are fixed (fig. 243), the stems of which are horizontal, and are bent at right angles near the bulbs. The upper one is a mercury, and the lower an alcohol, thermometer. In the maximum thermometer there is a short rod of glass or hard wood which serves as an index, and moves freely in the tube. The thermometer being placed horizontally, when the temperature rises the mercury pushes the index before it. But as soon as the mercury contracts the index remains in that part of the tube to which it has been moved, for there is no adhesion between the iron and the mercury. In this way the index registers the highest temperature which has been obtained; in this figure this is 13°. In the minimum thermometer there is a short piece of glass shaped like a dumb-

bell within the liquid column which serves as index. When it is at the end of the column of liquid, and the temperature falls, the column contracts and carries the index with it until it has reached the greatest contraction. When the temperature rises, the alcohol expands, and, passing between the sides of the tube and the index, does not displace the latter. The position of the index gives, therefore, the lowest temperature which has been reached The instrument is *set* by holding the tubes vertical until the indexes A and B have fallen to the surfaces of their respective liquids. It will be observed that in each tube the index is in contact with the *convex* surface of the liquid.

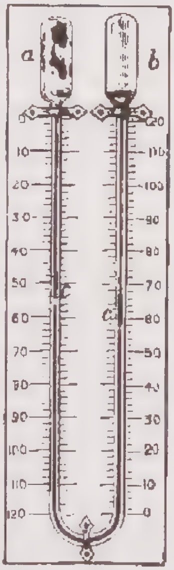


Fig. 244.

Sixe's thermometer (fig. 244) is not only a maximum and minimum, but gives a double reading, and therefore corrects itself. It consists of a U-shaped glass tube with a bulb at each end. Mercury occupies the bend. The bulb *a* and the left-hand stem down to the mercury are filled with alcohol, which also occupies the right-hand stem above the mercury and a part of the bulb *b*. Alcohol vapour and air fill the remainder of *b*. In the alcohol in each stem is an iron index which may be moved up and down by a magnet, and is kept in position by a bit of horse-hair attached to it. The expanding substance is the alcohol in *a*. When the temperature rises this expands and pushes the mercury down in the left, up in the right limb, and the index in front of it. When the temperature falls the alcohol in *a* contracts and the mercury follows it, pushing up the index in the left limb towards *a*. Breaks in the liquid column are prevented by the pressure of the air and alcohol vapour in *b*. The highest and lowest temperatures reached since the instrument was set are seen from the positions of the indexes in the right and left limbs respectively. The graduation of the instrument illustrated in fig. 244 is in degrees Fahrenheit.

One of the most important of the uses of the thermometer is in observing the temperature of the body. This, which is usually 98°·4 F., may vary within a degree or so even in perfectly healthy persons, but greater variations indicate some disturbance, and the

thermometer has become a most valuable criterion of the existence and course of diseases, more especially those of a febrile character. For determining the temperature of the body a special kind of maximum thermometer is used. It is graduated in Fahrenheit degrees, and shows only those portions of the scale which have to be observed (fig. 245). Such thermometers are called *clinical thermometers*. These thermometers are generally constructed on the so-called Negretti principle. The tube is very much contracted at a point near the bulb, as shown in the figure. As the temperature rises the mercury freely passes the constriction, but on cooling the mercury column breaks at this point, the part

Fig. 245

below receding into the bulb, while that above remains practically constant in length. Thus the physician need be in no hurry to read the temperature after the instrument has been withdrawn from the mouth. To be reset the thermometer is held in the hand and sharply jerked. The momentum of the mercury can thus be made to overcome the friction at the narrow part of the tube, and continuity is re-established between the mercury in the bulb and that in the tube.

222. **Pyrometers.**—The name *pyrometers* is given to instruments for measuring temperatures so high that mercurial thermometers could not be used. None of the older contrivances for this purpose give an exact measure of temperature, and the methods now used are based either on the expansion of gases or on alterations in the electric resistance of bodies, or on thermo-electricity (Book VIII. ch. xiii).

CHAPTER II

RADIATION OF HEAT

223. **Radiant heat.**—If we stand in front of a fire, or expose ourselves directly to the sun's heat, we experience a sensation of warmth which is not due to the temperature of the air; for if a screen be interposed the sensation immediately disappears, which would not be the case if the surrounding air had a high temperature. Hence bodies can send out rays which excite heat, and which penetrate through the air without heating it, just as rays of light pass through transparent bodies. Heat thus propagated is said to be *radiated*; and we shall use the term *ray of heat* or *thermal* or *calorific ray*, in a similar sense to that in which we shall afterwards use the term *ray of light* or *luminous ray*.

The rays of heat are not warm of themselves any more than the rays of light are luminous; they represent the direction in which heat is propagated, and only produce a heating effect when they fall upon a body and are absorbed by it. If they are transmitted they do not raise the temperature of a body. The upper layers of the atmosphere and the celestial spaces are no doubt at a lower temperature than any known on the earth.

If a stream of cold water be continuously passed through a hollow glass lens, on one side of which the sun's rays fall, a piece of tinder placed in the focus on the other side is easily ignited.

We shall find that the property of radiating heat is not confined to incandescent substances, such as a fire or a lamp, or a red-hot ball, but that bodies of all temperatures radiate heat. Thus a bottle full of hot water and a bottle full of cold water both emit heat; the quantity emitted depending upon the difference between the radiating body and that of the surrounding space.

224. **Laws of radiation.**—The radiation of heat is governed by three laws.

I. *Radiation takes place in all directions from a body.* If a thermometer be placed in different positions round a heated body,

it indicates everywhere a rise in temperature; at equal distances from the source of heat it indicates the same rise in temperature.

II. *Heat is propagated in right lines.* For, if a screen be placed in the right line which joins the source of heat and the thermometer, so as to stop the rays, the latter is not affected.

But in passing obliquely from one medium into another, as from air into glass, thermal, like luminous, rays become deviated, an effect known as *refraction.* The laws of this phenomenon are the same for heat as for light, and they will be more fully discussed under the latter subject.

III. *Radiant heat is propagated in a vacuum as well as in air.* This is directly demonstrated by the following experiment:—

In the bottom of a glass flask a thermometer t is fused in such a manner that its bulb occupies the centre of the flask (fig. 246). The neck of the flask is next carefully narrowed by means of the blowpipe, and then, the apparatus having been suitably attached to an air-pump, a vacuum is produced in the interior. This having been done, the tube is sealed by the blow-pipe at the narrow part. On immersing this apparatus in hot water, or on bringing near it some hot charcoal on a flame, the thermometer is at once seen to rise. This could only be due to radiation through the vacuum in the interior, for glass is so bad a conductor that the heat could not travel with sufficient rapidity through the sides of the flask and the stem of the thermometer to produce the effect observed.

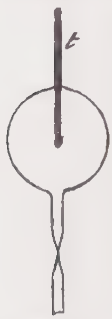


Fig. 246.

225. **Causes which modify the intensity of radiant heat.**—*The intensity of radiant heat is proportional to the temperature of the source.*

The first law is demonstrated by placing a metal box containing water at 10°, 20°, or 30°, successively at equal distances from the bulb of a differential thermometer. The temperatures indicated by the latter are then found to be in the same ratio as those of the box; for instance, if the temperature of that corresponding to the box at 10° be 2°, those of the others will be 4° and 6° respectively.

The intensity of radiant heat at any point is inversely as the square of the distance of the point from the source.

Let us imagine a hollow sphere $a\ b$ (fig. 247) of any given radius, and that at its centre there is a constant source of heat C. Each unit of surface of the inner face of the sphere will receive a definite

quantity of heat. Now if the radius of the sphere is doubled and equal to *c f*, it follows from a well-known geometrical theorem that the inner surface is four times as great. But as, by supposition, the source of heat remains constant, each unit of surface must now receive only *one-fourth*.

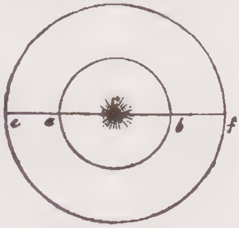


Fig. 247.

It should be observed that this principle only holds for heat rays *diverging from a point*; for *parallel* rays the intensity is the same at all distances apart from absorption by the medium.

226. **Interchange of heat among all bodies.**—Owing to the radiation which is continually taking place in all directions round a body, there is a continual interchange of heat. If the bodies are all at the same temperature, each one sends to the surrounding ones a quantity equal to that which it receives, and their temperatures remain stationary. But if their temperatures are unequal, since the hot bodies emit more heat than they receive, they therefore sink in temperature; while, as the bodies of lower temperatures receive more heat than they emit, their temperature rises; thus the temperatures are all ultimately equal. The radiation does not stop; it goes on, but without loss or gain from each body, and this condition is accordingly known as the *mobile equilibrium of temperature.*

From what has been said it will be understood that bodies, placed in our rooms, all tend to assume a uniform temperature; generally speaking this is not the case, for many causes concur in cooling one set, and in heating the others. Thus bodies, placed near a wall, cooled by the outer air, find a cause for cooling. Those, on the contrary, which are at the top of the room tend to acquire a higher temperature; for, as heated air rises, the layers nearest the ceiling are always hotter than the lower ones.

From this continual interchange of heat there is necessarily a limit to the cooling of bodies; for they always tend to resume on the one hand what they lose on the other. To have an indefinite cooling, a body should be suspended in space, not receiving heat from any body. As it would then lose heat without acquiring any, it must eventually reach the absolute zero of temperature, a condition in which its particles would have lost all their vibratory motion and have become absolutely motionless.

CHAPTER III

REFLECTION OF HEAT. REFLECTING, ABSORBING, AND EMISSIVE POWERS

227. **Law of the reflection of heat.**—When the rays emitted by a source of heat fall upon the surface of a body, they are divided generally into two parts: one, which passing into the mass of a body is absorbed, and raises the temperature; the other, which darts off from the surface like an elastic ball striking against a hard body; this is expressed by saying that these rays are *reflected*. Thus let A be the source of heat, a cubical box filled with hot water (fig. 248), and near it a screen which does not allow

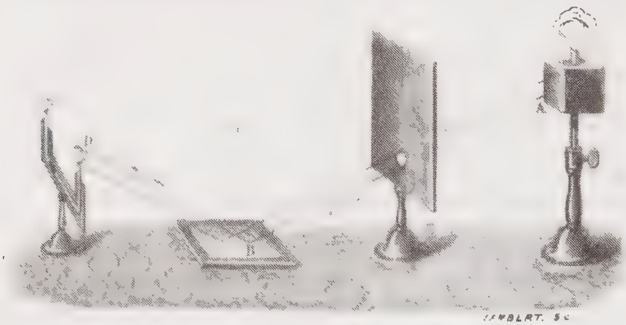


Fig. 248.

heat to pass, but near the bottom of which is an aperture. If behind this screen a polished surface, B, be placed, against which the rays from the cube strike, and beyond this again a differential thermometer, D (220), the latter indicates an increase of temperature when one of its bulbs is so placed that it receives the rays reflected by the polished body. In this experiment, rays like A B, which fall on the reflecting surface, are called *incident* rays, from a

Latin word which signifies 'to fall upon;' and the *angle of incidence* is not the angle which the incident rays make with the reflecting surface, but the angle ABC which they make with a straight line, BC, perpendicular to this surface. In like manner the angle CBD, which the reflected rays make with the same straight line, is called the *angle of reflection.*

The reflection of heat is always expressed by the law that *the angle of reflection is equal to the angle of incidence.* We shall subsequently see that the reflection of light follows the same law.

228. **Reflection of heat from concave mirrors.**—The effects of the reflection of heat may be very powerful when it takes place from the surface of *concave mirrors*, which are spherical surfaces of glass or of metal. A group of rays, starting from a point and

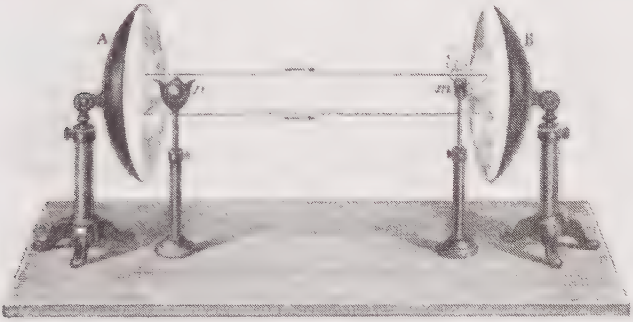


Fig. 249.

falling upon a concave mirror, converge after reflection to a single point, to which the name *focus* (from the Latin word for a *hearth*) is applied, to express the great quantity of heat which is concentrated there.

In treating of light we shall describe in detail the properties of the focus of concave mirrors; for the present it will be sufficient to describe experiments which demonstrate the great intensity which radiant heat may acquire when concentrated in these points. Fig. 249 represents an experiment which is frequently made in lectures on physics. Two reflectors, A and B, are arranged at a distance of 4 to 5 yards, so that their axes coincide. In the principal focus of one of them is placed a small basket *n*, containing a red-hot iron ball; in the corresponding focus of the other an inflammable

body, such as gun-cotton, or phosphorus, *m*. The rays emitted from the focus *n* are first reflected from the mirror A in a direction parallel to the axis ; and, impinging on the other mirror, B, are reflected so that they converge to the focus *m*. That this is so is proved by the fact that the inflammable substance placed in this point takes fire, which is not the case if it is above or below it.

A similar but more powerful effect is produced when the concave mirror is so placed that the sun's rays strike directly against it ; if then a combustible substance, such as paper, wood, cork, etc., be held by means of a pincette in the focus, these bodies are seen to take fire. The effect produced depends on the magnitude of the mirror. With a mirror having an *aperture* of 6 feet—that is, the distance from one edge to the other—copper and silver are soon melted ; and silicious stones and flints have been softened and even melted.

In consequence of the high temperatures produced in the foci of concave mirrors and of the facility with which combustible bodies may be ignited there, they have been called *burning mirrors*. Buffon constructed burning mirrors of a number of silvered plane mirrors, each about 8 inches long by 5 broad. They could be turned independently of each other in such a manner that the rays reflected from each coincided in the same point. With 168 such mirrors and a hot summer's sun Buffon ignited a plank of tarred wood at a distance of 70 yards.

229. **Reflecting power of various substances.**—It has been seen that the heat which falls upon a body is always divided into two parts—one which is reflected from the surface, and the other which passes into the mass of the body, and raises its temperature. The quantities of heat thus absorbed, or reflected, vary in different substances ; one set reflects much and absorbs little, which is expressed by saying that they have a great *reflecting power* ; others, on the contrary, reflect very little heat, but absorb a great deal, and are therefore spoken of as having great *absorbing power*. It is clear that these properties are the inverse of each other, for any body which absorbs much heat can reflect but little, and conversely.

In order to compare the reflecting powers of various substances, Leslie took as a source of heat a tin-plate cube full of boiling water, which he placed in front of a concave mirror (fig. 250). The rays emitted from the cube and falling upon the reflector converged after reflection to the focus F. In front of and a short distance from this were placed successively small square plates of paper, glass,

metal—in short, of all the substances whose reflecting powers were to be examined. After reflection from the mirror, the rays, as shown in the drawing, were reflected a second time from these plates, and finally impinged against the bulb of a differential thermometer, which was shielded in such a way that only rays reflected from the small plate could reach it. Now, in this experiment the source of heat was the same, as was also the distance from the reflector; yet the thermometer gave very different indications according to

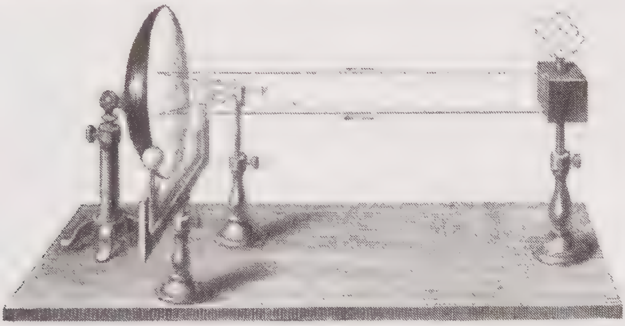


Fig. 250.

the material of which the small plates were formed. The temperature was highest when the plate was made of polished brass, which metal is therefore the best reflector. The reflecting power of silver is only $\frac{9}{10}$ that of brass; that of tin $\frac{8}{10}$; of glass $\frac{1}{10}$. Water and lampblack were found to be destitute of reflecting power, for when the plates were coated with lampblack, or moistened with water, the thermometer indicated no increase in temperature, showing that it had received no heat.

230. **Absorbing power.**—In order to compare the absorbing powers of various substances, Leslie arranged the experiment as shown in fig. 251. The source of heat and the reflector being the same as in the preceding experiment, the differential thermometer was placed in the focus, where it received directly all the heat reflected by the mirror. The surface of the *focal* bulb was altered for each experiment by coating it successively with various materials, paper, tinfoil, gold, silver, copper, and leadfoil; it was also coated with a thin layer of lampblack; it was moistened, and so on. It was thus found that when the focal bulb was coated with lampblack, or with water, the thermometer indicated the highest

temperatures ; whence it was concluded that lampblack and water have the greatest absorbing power. The lowest temperature was exhibited when the bulb was coated with thin metal foil, more especially with silver ; thus indicating that bright metallic surfaces are the least absorbent of the substances experimented on when the source is at the temperature of boiling water (233). The result was arrived at, which could indeed be foreseen, that those bodies which best reflect heat absorb it least ; and that, conversely, the best absorbers are the worst reflectors.

231. **Emissive power.**—The *emissive* or *radiating* power is the property bodies have of emitting more or less easily the heat they contain ; it is the inverse of the absorbing power.

Leslie compared the emissive powers of various bodies by means of the apparatus represented in fig. 251. The focal bulb of the

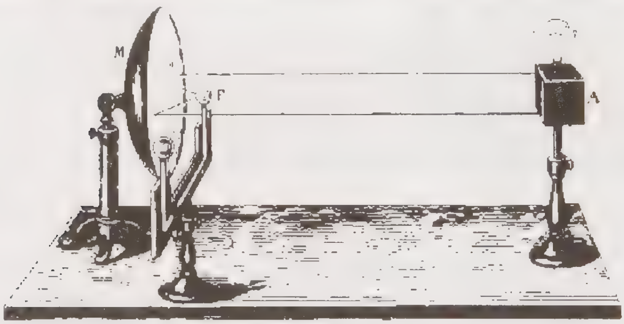


Fig. 251.

thermometer was left uncoated, and the various substances were applied successively to the sides of the tin cube. One of them, for instance, was left in its ordinary condition ; the second was coated with lampblack ; to the third a sheet of white paper was fixed, and to the fourth a glass plate.

Turning first of all the blackened face towards the reflector, the thermometer indicated a considerable increase of temperature, thus showing that the cube sent much heat towards the reflector. Turning then successively the other faces towards the reflector, it was found that the paper side emitted less heat than the blackened face, but more than the glass side, which in turn emitted more than the tin side.

Working in this manner, Leslie found that lampblack has the

greatest emissive power, then paper, then ordinary glass, then the metals. The order of their emissive powers is thus the same as that of their absorbing powers. It is thus concluded that bodies which best absorb heat also radiate best; and it has been proved that for each substance the emissive power is equal to the absorbing power.

232. **Causes which modify the reflecting, absorbing, and radiating powers.**—As the radiating and absorbing powers are equal, any cause which affects the one affects the other also. And as the reflecting power varies in an inverse manner, whatever increases this diminishes the radiating and absorbing powers, and *vice versa.*

It has been already stated that these different powers vary with different bodies, and that metals have the greatest reflecting power and lampblack the feeblest. In the same body these powers are modified by the degree of polish, the density, the thickness of the radiating substance, the obliquity of the incident or emitted rays, and, lastly, by the nature of the source of heat.

The relation between the absorbing and radiating powers is well illustrated by the following experiment (fig. 252), which represents what is in effect a differential thermometer (220) with polished metal canisters, B and C, instead of glass bulbs. These are connected by a glass tube in which stands coloured liquid. Between them is a metal canister, A, which can be filled with hot water. The faces of B and of A which look to the right are coated with lampblack; those of C and A which face the left are bright and polished. Thus of two opposite faces one is black and the other bright; hence, when the cylinder A is filled with hot water, its white face radiates towards the black face of B, and its black face towards the white face of C, and the liquid in the stem does not move, showing that they are at the same temperature. On the one hand the greater emissive power of the black face of A is compensated by the smaller absorptive power of the white

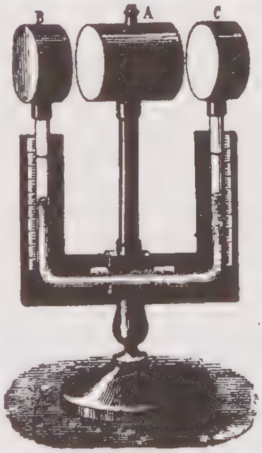


Fig. 252.

face of C; while on the other hand the feebler radiating power of

the white face of A is balanced by the greater absorbing power of the black face of B.

If, however, the canister be turned round so that the two black or the two bright faces are opposite one another, the liquid at once moves.

The absorbing power varies with the inclination of the incident rays. It is greatest at right angles ; and it diminishes in proportion as the incident rays are less perpendicular. This is one of the reasons why we receive more heat from the sun in summer than in winter ; because, in the former case, the sun's rays are less oblique.

The radiating power of gaseous bodies in a state of combustion is feeble, as is seen by bringing the bulb of a thermometer near a hydrogen flame, or the flame of an ordinary Bunsen burner, the temperature of which is very high, but which is almost destitute of illuminating power. If a platinum spiral be placed in this flame, it assumes the temperature of the flame, and radiates a considerable quantity of heat, as is indicated by the thermometer. For a similar reason the flames of oil and of gas lamps radiate more than a hydrogen flame in consequence of the carbon which they contain, and which, not being entirely burned, becomes white-hot in the flame.

An important application of this is made in the *Auer-Welsbach* light. Over such a non-luminous burner as that of Bunsen, a delicate mantle or cap of certain rare earths is suspended. They have the property of resisting the high temperature of the flame without any appreciable loss by volatilisation, and of thus emitting a light of dazzling brightness. It is stated that the luminosity thus obtained is six times as great as that produced by an equal volume of gas burned in an ordinary luminous burner.

The absorbing power of a body is also influenced by the nature of the source of heat. Thus, for the same quantity of heat emitted, a surface coated with white lead absorbs twice as much, if the heat comes from a cube filled with hot water, as it does if the heat is that of a lamp. Lampblack, on the contrary, under the same conditions, absorbs the same amount of heat whatever be the source.

233. **Different kinds of heat. Diathermancy.**—Just as different substances possess the power of allowing the rays of light to pass through them to different extents, and are said to be more or less *transparent* (325), so also modern investigation has shown that all

bodies do not allow the rays of heat to traverse them with equal facility, and are therefore said to be more or less *diathermanous.* For instance, the metals are just as *athermanous* for heat rays as they are *opaque* for the rays of light. On the other hand, rock-salt stands in the same relation to heat rays that a perfectly colourless and transparent body, such as glass, does to luminous rays. It is perfectly diathermanous.

One and the same substance may be diathermanous to varying extents for *heat from different sources.* Thus colourless glass allows the sun's rays to pass through it with facility, but less so the heat emitted by a flame, or by an incandescent body, and far less, again, the invisible or *obscure* heat of a cube filled with boiling water, which is known as a *Leslie's cube* (229). Water allows the sun's rays to traverse it partially, but stops the obscure heat. Again, alum is colourless and transparent for light, but almost entirely athermanous for obscure rays.

A body which is opaque for light may be diathermanous for certain kinds of heat. Thus, a solution of iodine in bisulphide of carbon is perfectly opaque for the rays of light, but is traversed by obscure heat-rays with facility.

In investigating the diathermancy of bodies, Melloni used the thermopile and galvanometer, for a description of which we must refer to Book VIII., chapter xiii. He first of all placed the thermopile at a certain distance from a source of heat, and, having observed the deflection of the galvanometer, he determined to what extent this was enfeebled by interposing various bodies, such as plates of glass, alum, and rock-salt. In like manner he used various sources of heat—for instance, the sun, an oil or spirit lamp, a red-hot spiral of platinum wire, a heated blackened metal plate, or a Leslie's cube ; and he concluded that there are *different kinds of heat-rays* or different *colours of heat*, with regard to which various diathermanous substances behave just as coloured transparent substances do in regard to different kinds of light. Thus, when white light traverses red glass, only the red rays are transmitted, all other kinds being absorbed. If this red light falls on another red glass, it traverses it without being weakened, if we neglect the portion lost by reflection ; but it is completely absorbed by blue glass. Similar results are met with in regard to the rays of heat—for instance, heat which has passed through a glass plate would traverse another plate without much loss, but would be almost completely stopped by a plate of alum.

234. **Applications.**—The property which bodies possess of absorbing, emitting, and reflecting heat meets with numerous applications in domestic economy and in the arts. Leslie stated that white bodies reflect heat very well, and absorb very little, and that the contrary is the case with black substances. This principle is not universally true, as Leslie supposed—for example, white lead has as great an absorbing power for non-luminous rays as lamp-black—but it holds good in regard to absorbents like cloth, cotton, wool, and other organic substances when exposed to luminous heat, such as that of the sun's rays. Accordingly, the most suitable coloured clothing for summer is just that which experience has taught us to use—namely, white, for it absorbs less of the sun's rays than black clothing, and hence feels cooler.

The polished fire-irons before a fire are cool whilst the black fender is often unbearably hot. If a liquid is to be kept hot as long as possible, it must be placed in a brightly polished metal vessel, for then, the emissive power being less, the cooling is slower. For this reason it is advantageous that the steam-pipes, etc., of locomotives should be kept brightly polished.

Snow is a powerful reflector, and therefore neither absorbs nor emits much heat : owing to its small emissive power it protects from cold the ground and the plants which it covers ; and owing to its small absorbing power it melts but slowly during a thaw. A branch of a tree, a bar of metal, a stone in the midst of a mass of snow, accelerate the fusion by the heat they absorb, which they radiate about them.

In the Alps the mountaineers accelerate the fusion of the snow by covering it with earth, which increases the absorbing power.

Metal and other cooking-vessels should be black and rough on the outside, for then their absorbing power is greater and they become heated more rapidly. If their surface be bright and polished, a greater quantity of fuel is required to heat them ; this is what is seen in vessels of silver and of white porcelain. In common unglazed earthenware, liquids are more rapidly heated, but also more rapidly cooled.

It is observed that grapes and other fruits ripen sooner when they are placed close to a black wall (mortar mixed with lamp-black). This arises from the fact that from the great absorbing power of the wall, as well as from its great emissive power, it becomes more highly heated under the influence of the sun, and gives up more heat to the fruit.

Glass is used for fire-screens ; for, while it allows the cheerful light of the fire to pass, it stops most of the heat from this source. It is, however, very transparent for the heat of the sun, allowing almost all its light and heat to pass.

In gardens, the use of glass shades and of greenhouses depends on the diathermancy of glass for heat from luminous rays, and on its athermancy for obscure heat. The heat which radiates from the sun is mainly of the former class, and penetrates the glass ; but by its contact with the earth is changed into obscure heat, which as such cannot retraverse the glass. This explains the manner in which greenhouses accumulate heat, and also the great warmth in summer of rooms with glass roofs.

A mercury thermometer the bulb of which is blackened by being coated with lampblack will indicate a rise of temperature where an ordinary one is unaffected. If one of the bulbs of a differential thermometer be coated with lampblack, and the other be left unaltered, and both be exposed to the same source of heat, the blackened one will show the higher temperature.

A piece of bright tinfoil upon which the sun's rays are brought to a focus by means of a lens will be fused with difficulty, or not at all ; but if the surface is coated with lampblack, it will melt in the focus at once.

A pencil of the sun's rays, concentrated by a glass lens, and allowed to fall on the glass bulb of a differential thermometer, does not raise its temperature, for the rays which would be absorbed by the glass have already been cut off by the lens, and therefore the rays, thus sifted, pass through the bulb without action.

CHAPTER IV

CONDUCTING POWER OF BODIES FOR HEAT

235. **Conducting power of solids.**—In the phenomena of radiation which have been considered, heat is transmitted from one body to another through space, without raising the temperature of the medium through which it passes. Heat may also be propagated through the mass of a body, from molecule to molecule. This interval propagation in the mass of a body is due to the *conductivity*, or *conducting power*; and *good conductors* are those bodies which readily transmit heat in their mass, while those through which it passes with difficulty are called *bad conductors*.

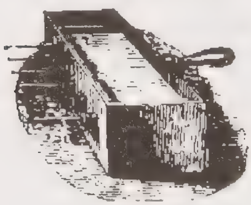


Fig. 253.

In order to compare the conducting power or *conductivity* of different solids, Ingenhaus constructed the apparatus, known still by his name, and represented in fig. 253. It is a metal trough in which, by means of tubulures and corks, are fixed rods of the same dimensions, but of different materials—for instance, iron, copper, wood, glass. These rods extend to a slight distance in the trough, and the parts outside are coated with wax, which melts at 61°. The box being filled with boiling water, it is observed that the wax melts to a certain distance on the metal rods, while on the others there is scarcely any trace of fusion. The conducting power is evidently greater in proportion as the wax has fused to a greater distance. By these and other experiments it has been ascertained that metals are the best conductors; then—but after a long interval—marble, porcelain, brick, wood, glass, etc.

Organic substances conduct heat badly. De la Rive and De Candolle show that woods conduct better in the direction of their

fibres than in a transverse direction, and have remarked upon the influence which this feeble conducting power, in a transverse direction, exerts in preserving a tree from sudden changes of temperature, enabling it to resist alike a sudden abstraction of heat from within, and the sudden accession of heat from without. Tyndall has also shown that this tendency is aided by the low conducting power of the bark, which is in all cases less than that of the wood.

Cotton, wool, straw, bran, powdered gypsum, etc., are all bad conductors.

236. **Conducting power of liquids. Manner in which they are heated.**—Liquids, with the exception of mercury, which is a metal, are all bad conductors of heat. They conduct so imperfectly that Rumford assumed water to be entirely destitute of conducting power. But the fact that water, as well as other liquids, does conduct heat, though only to a small extent, has been established by the most careful and accurate experiments.

From their small conducting power, liquids are not heated in the same manner as solids. If heat be applied to a solid, whether on the top, the bottom, or the sides, it is transmitted from layer to layer, and the whole mass becomes heated. This is not the case with a liquid: if it is heated at the top, the heat is only propagated with extreme slowness, and it cannot be completely heated throughout; indeed, if the experiment be made as represented in fig. 254, the top layer of water may be heated to boiling, while at a little distance there is no appreciable increase of temperature. But if it be heated at the bottom, the temperature of the liquid rapidly rises. This, however, is not owing to its conductivity, but to ascending and descending currents, which are produced throughout the whole mass of liquid.

Fig. 254.

The existence of these currents may be demonstrated by placing in the water a powder of nearly the same density—for instance, oak sawdust—and then gently heating the vessel at the

bottom (fig. 55). As the lower layers of the liquid become heated they expand and rise, while the upper layers, which are colder and therefore denser, sink, and take the place of the first; these in their turn become heated, rise, and so on, until the entire mass is heated. These currents are evident from the sawdust, which is seen to rise slowly in the centre, and to redescend near the edges. This mode of heating is said to be by *convection*.

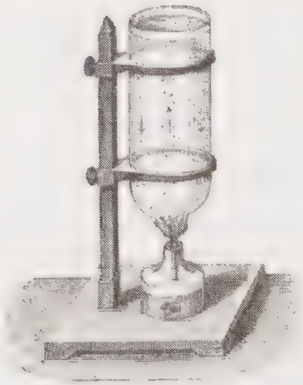


Fig. 255.

237. **Conductivity of gases.** Gases are extremely bad conductors of heat; but this fact cannot be easily demonstrated by experiment, owing to the extreme mobility of their particles. For, so soon as they are heated in any part of their mass, expansions and currents are produced, in virtue of which the heated parts mingle with the cold ones; hence a general elevation of temperature, which we might be tempted to consider as due to conductivity, but which is really due to *convection*. When, however, gases are hindered in their motion, their conductivity seems extremely small, as shown by many examples in the following article.

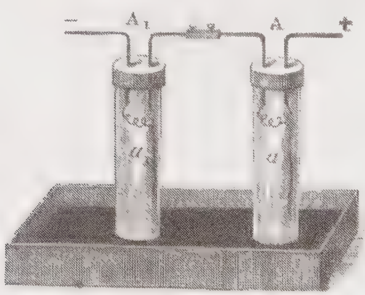


Fig. 256.

That there is a difference in gases as regards their conductivity for heat may be seen from the following experiment. A_1 and A (fig. 256) are two similar vessels, open at the bottom, standing in a mercury trough, one of them containing air and the other hydrogen. In the caps stout copper wires are inserted which are joined by fine platinum spiral wires a_1 and a. When the wires are connected with the poles of a voltaic battery, an electric current passes through the spirals. The

electric current, we shall afterwards see (476), has the property of heating a wire through which it passes, and the rise of temperature is higher the thinner the wire. On passing the current it will be found that while the spiral in air is heated to redness, the one in hydrogen remains quite dull. Now, the heat produced by the passage of the current is the same in both the wires, for they are exactly alike, and accordingly the difference can only be due to the fact that the heat is more rapidly carried away by the hydrogen than by the air; in other words, that hydrogen is a better conductor. The conductivity of air is $\frac{1}{25000}$ that of silver.

238. **Applications.**—The greater or less conductivity of bodies for heat meets with numerous applications. If a liquid is to be kept warm for a long time, it is placed in a vessel and packed round with non-conducting substances, such as shavings, straw, bruised charcoal. Similarly, water-pipes and pumps are wrapped in straw at the approach of frost. The same means are used to hinder a body from becoming heated. Ice is transported in summer by packing it in bran, or by folding it in flannel.

Double walls constructed of thick planks having between them any finely divided materials, such as shavings, sawdust, dry leaves, etc., retain heat extremely well; they are likewise advantageous in hot countries, for they prevent its access. If a layer of asbestos, a very fibrous substance, is placed on the hand, a red-hot iron ball can be held without inconvenience. Red-hot iron balls can be wheeled to the gun's mouth in wooden barrows partially filled with sand. Lava has been known to flow over a layer of ashes underneath which was a bed of ice, and the non-conducting power of the ashes has prevented the ice from fusion. Snow forms a covering which protects seed and young grain from frost. In fire-proof safes, the hollow sides are filled with wood-ashes, or powdered gypsum or alum.

The clothes which we wear are not warm in themselves; they only hinder the body from losing heat, in consequence of their spongy texture and the air they enclose. The warmth of bed-covers and o counterpanes is explained in a similar manner. Double windows are frequently used in cold climates to keep a room warm—they do this by the non-conducting layer of air interposed between them. For the same reason two shirts are warmer than one of the same material but twice as thick. Hence, too, the warmth of furs, eiderdown, etc.

That water boils more rapidly in a metallic vessel than in one of

porcelain of the same thickness ; that a burning piece of wood can be held close to the burning part with the naked hand, while a piece of iron heated at one end can only be held at a great distance, are easily explained by reference to their various conductivities.

The sensation of heat or cold which is experienced when we touch certain bodies is materially influenced by their conductivity. If their temperature is lower than ours, they appear colder than they really are, because, from their conductivity, heat passes away from us. If, on the contrary, their temperature is higher than that of our body, they appear warmer, from the heat which they give up at different parts of their mass. Hence it is clear why carpets, for example, are warmer than wooden floors, and why the latter, again, are warmer than stone floors.

The small conducting power of felt is used in the construction of the *Norwegian stove*, which consists merely of a wooden box with a thick lining of felt. In the centre is a cavity in which can be placed a stew-pan provided with a cover. On the top of this is a lid, also made of felt, so that the pan is surrounded by a very badly conducting envelope. Meat, with water and suitable additions, is placed in the pan, and the contents are then raised to boiling. The whole is then enclosed in the box, and left to itself; the cooking will go on without fire, and after the lapse of several hours it will be quite finished. The cooling down is very slow, owing to the bad conducting power of the lining ; at the end of three hours the temperature is usually found not to have sunk more than from 10° to 15°.

The closer the contact of the hand with a substance, the greater is the difference of temperature felt. With smooth surfaces there are more points of contact than with rough ones. A hot glass rod feels hotter than a piece of rusted iron of the same temperature, although the latter is a better conductor. The closer the substance is pressed the more intimate the contact ; an ignited piece of charcoal can be lifted by the fingers, if it is not closely pressed.

CHAPTER V

MEASUREMENT OF THE EXPANSION OF SOLIDS, LIQUIDS, AND GASES

239. **Expansion of solids.**—The expansion of bodies by heat being a general effect which is experienced by all bodies, it will be readily understood that the determination of the amount of this expansion is a problem of great importance, both in its purely scientific and in its practical aspect. We shall first describe the method of determining the expansion of solids. We have already seen that the expansion of solids may be as regards either the length or the volume. Hence the investigation of the expansion of solids may be divided into two parts, the first relating to *linear*, and the second to *cubical* expansion.

Linear expansion. In order to compare with each other the expansions of bodies, the elongation is taken which a certain length of the substance undergoes when it is heated from zero to 1°, and the ratio of this elongation to the original length is called the *coefficient of linear expansion.* The coefficients of a great number of substances were accurately determined towards the end of the last century by Lavoisier and Laplace. They took a bar of the substance to be experimented on, placed it in melting ice, and then accurately measured its length. Having placed it then in a bath of boiling water, they again measured its length. They thus obtained the total expansion between zero and 100°—that is, for an increase of temperature of 100 degrees. This divided by 100, and by the length of the bar at zero, gave the coefficient of linear expansion. In this manner the following numbers were obtained :

Coefficients of linear expansion for 1° between 0° and 100° C.

White glass	0·00000861	Bronze	0·000018167
Platinum	0·00000884	Brass	0·000018782
Steel	0·00001079	Silver	0·000019097
Iron	0·00001220	Tin	0·000021730
Gold	0·00001466	Lead	0·000028575
Copper	0·00001718	Zinc	0·000029417

T 2

It will be seen from this table that the coefficients of expansion are in all cases very small. Thus, when we say that the coefficient of expansion of copper is 0·000017, we mean that a rod of this metal when heated through one degree will expand by 17 millionths of its length—that is to say, a rod of copper 1,000,000 feet in length would be longer by 17 feet when heated through one degree.

At temperatures below zero, ice, like other bodies, is expanded by a rise, and is contracted by a fall in temperature. Its coefficient of linear expansion is 0·000053, or nearly twice that of lead or zinc. Ice is, indeed, the most expansible of all known solids.

Cubical expansion. The *coefficient of cubical expansion* of a substance is the ratio of the increase in volume to its original volume for a rise of temperature of one degree. Calculation shows that the coefficient of cubical expansion of a solid may with sufficient accuracy be taken as three times the coefficient of its linear expansion; and these coefficients may therefore be obtained by multiplying the above numbers by three.

240. **Applications of the expansion of solids.**—In the arts we meet with numerous examples of the influence of expansion. (i.) The bars of furnaces must not be fitted tightly at their extremities, but must be free, at least at one end, otherwise in expanding they would exert sufficient force to split the masonry. (ii.) In making railways, a small space is left between the successive rails, for, if they touched, the force of expansion would cause them to curve, or would break the chairs. (iii.) Hot-water pipes are fitted to one another by means of telescopic joints, which allow room for expansion. (iv.) If a glass is heated or cooled too rapidly—say, in the inside—it cracks: this arises from the fact that glass being a bad conductor of heat, the sides become unequally heated, and consequently unequally expanded, and the strain thereby produced may be sufficient to cause a fracture.

When bodies have been heated to a high temperature, the force produced by their contraction on cooling is very considerable: it is equal to the force which is needed to compress or expand the material to the same extent by mechanical means. According to Barlow, a bar of malleable iron a square inch in section is stretched $\frac{1}{10000}$ of its length by a weight of a ton; the same increase is produced by a rise of temperature of about 9° C. A difference of 45° C. between the cold of winter and the heat of summer is not unfrequently experienced in this country. In that range a wrought-iron bar ten inches long and a square inch in section will vary in

length by $\frac{1}{100}$ of an inch, and will exert a strain, if its ends are securely fastened, of five tons.

An interesting laboratory experiment, showing the great contractile force of metals, may be made with the apparatus represented in fig. 257, which consists of a massive cast-iron frame with notches in the uprights. A wrought-iron bar, with a screw at one end and a loop at the other, having been raised almost to a red heat, a short rod of cast iron is passed through the loop, and the bar placed in the frame and screwed up. As the bar contracts on cooling, the force is so great that the short rod snaps. To cool the bar rapidly cold water may be poured upon it.

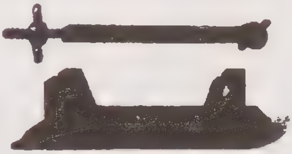


Fig. 257.

An application of this contractile force is seen in the mode of securing the tyres on wheels. The tyre, being made red-hot, and thus considerably expanded, is placed on the circumference of the wheel, and then cooled. The tyre, when cold, clasps the wheel with such force as not only to secure itself on the rim, but also to press home the ends of the spokes into the felloes and nave. Another interesting application was made in the case of a gallery at the Conservatoire des Arts et Métiers in Paris, the walls of which had began to bulge outwards. Iron bars were passed across the building, and screwed into plates on the outside of the walls. Each alternate bar was then heated by means of lamps, and when the bar had expanded it was screwed up. The bars, being then allowed to cool, contracted, and in doing so drew the walls together. The same operation was performed on the other bars.

241. **Spiral thermometer.**—An interesting example of the application of the expansion of solids is met with in the form of a maximum and minimum thermometer represented in fig. 258. It consists of a steel ribbon a yard long, rather less than half an inch wide, and about the twentieth of an inch thick, to which is soldered a brass ribbon of the same dimensions. The compound strip is bent in a spiral, *s*, the steel being outermost. One end is fixed; the other end, *b*, is free. At a certain definite temperature this end has a certain position. If the temperature rises, the brass expands more than the steel, and the free end is moved towards the left ; if the temperature sinks, it moves towards the right.

This motion of the spiral is transmitted to two indicators, *cd*

and *fg*, on which are small pins, *p* and *p*. If the temperature rises, the pin *p*, together with its index, *cd*, is pushed forward until the maximum temperature is reached, and, as there is a gentle friction, remains in that position. If, on the contrary, the temperature sinks, the index *fg* is moved to the right until the lowest temperature is obtained. The instrument is graduated specially by comparing its indications with the corresponding temperatures shown by a mercurial thermometer.

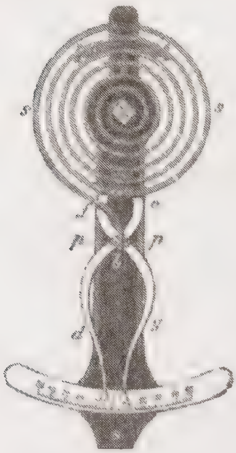


Fig. 258.

242. **Compensation pendulum.** — An important application of the expansion of metals has been made in *the compensation pendulum*. To understand the utility of such an arrangement, we must call to mind what has been said about pendulums (62)—namely, that their oscillations are *isochronous*—that is, are made in equal times—and that their application to the regulation of clocks depends upon this property. But we have also seen that the time of an oscillation depends on the length of the pendulum: the longer the pendulum, the more slowly it oscillates, and the shorter it is, the more rapidly does it oscillate. Hence a pendulum formed of a single rod terminated by a metal bob, *c*, as represented in fig. 63, could not be an exact regulator of time; for as the temperature rises it would lengthen, and the clock would go slower; the exact opposite would take place when it contracted by cooling. These inconveniences have been remedied by taking the remedy from the cause of the evil.

In fig. 259, which represents the *gridiron* pendulum, one of the forms of compensation pendulum, the ball, L, instead of being supported by a single rod, is supported by a framework consisting of alternate rods of steel and brass. In the figure the shaded rods represent steel; including a small steel strip, *b*, which supports the whole of the apparatus, there are six of them. The other rods, four in number, are of brass. The rod *i*, which supports the ball, is fixed at its upper end to a horizontal cross-piece; at its lower end it is free, and passes through the two circular holes in the lower horizontal cross-pieces.

Now, from the manner in which the vertical rods are fixed to the cross-pieces, it is easy to see that the elongation of the steel rods can only take place downwards, and that of the brass rods upwards. Consequently, in order that the pendulum may remain of the same length, it is necessary that the elongation of the brass rods shall tend to make the ball rise, by exactly the same distance that the elongation of the steel rods tends to lower it; a result which is attained when the sum of the lengths of the steel rods A is to the sum of the lengths of the brass rods B in the inverse ratio of the coefficients of expansion of steel and brass, a and b; that is, when $A : B = b : a$.

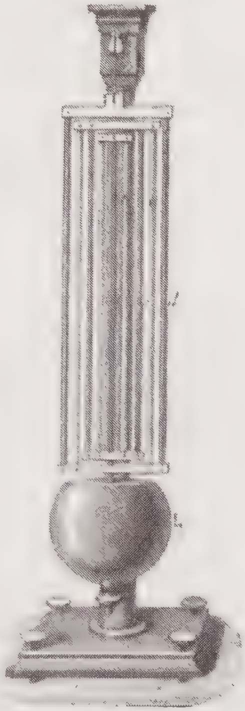


Fig. 259.

243. **Absolute and apparent expansion.**—We have already seen that liquids are more expansible than solids (213), which is a consequence of their feebler cohesion; but their expansibility is far less regular, and the less so the nearer their temperature approaches the boiling-point.

In solids, two kinds of expansion have to be considered, the linear and the cubical. Now, it is clear that the latter is the only kind of expansion which can be observed in the case of liquids. The expansion may be either *real* or *apparent*. The former is the real increase in volume which a liquid experiences when it is heated; while the latter is that which the eye actually observes—that produced in the vessel containing the liquid. Thus, in thermometers, when the liquid expands and rises in the stem, the apparent expansion is observed, which is less than the real or absolute expansion. For, while the mercury expands, the bulb of the thermometer does so too: its volume is greater, and hence the liquid does not rise so high in the stem as it would if the volume of the bulb were rigidly unaltered.

If a bulb of thin glass (fig. 260), provided with a narrow stem, containing some coloured liquid, be immersed in a beaker of hot water, *a*, the column of liquid in the stem at first sinks from the mark C′, at which it originally stood, to the mark C, but then immediately after rises, and continues to do so until the liquid inside has the same temperature as the hot water. The first sinking of the liquid is not due to its contraction ; it arises from the expansion of the glass, which becomes heated before the heat can reach the liquid ; but the expansion of the liquid soon exceeds that of the glass, and the liquid then ascends.

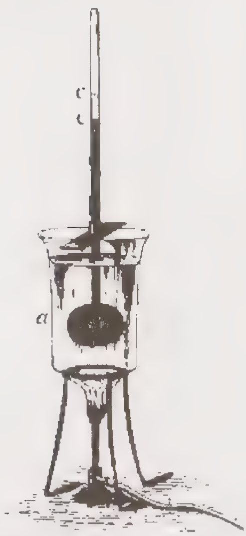


Fig. 260.

Hence, since, whatever be the nature of the material in which a liquid is contained, it has some expansibility, and always expands with the liquid, the apparent expansion is the only one directly observed in liquids.

The coefficient of expansion of a liquid is the increase which a unit volume experiences for a rise in temperature of one degree. The coefficient varies greatly with different liquids. In a glass vessel the apparent expansion of mercury is 1·5 part in ten thousand ; that of water is 4·6 parts—that is, three times as great ; alcohol is still more expansible, for its coefficient is 11·6 parts in ten thousand, or a little over 1 part in a thousand.

244. **Maximum density of water.**—Water presents the remarkable phenomenon that as its temperature sinks to 4° it contracts ; but from that point, although the cooling continues, it expands until the freezing-point is reached, so that 4° represents the point of greatest contraction of water, or what is called its *point of maximum density*.

These phenomena may be observed by comparing a water thermometer—one, that is to say, filled with water—with one of mercury ; both being exposed to a temperature gradually diminishing.

Hope used the following method to determine the maximum density of water. He took a deep vessel with two apertures in the side, in which he fixed thermometers (fig. 261), and having filled the vessel with water at 0°, he placed it in a room at a temperature of 15°. As the layers of liquid at the sides of the vessel became heated, they sank to the bottom, and the lower thermometer marked 4°, while that of the upper one was still at zero. Hope then made the inverse experiment: having filled the vessel with water at 15°, he placed it in a room at zero. The lower thermometer, having sunk to 4°, remained stationary for some time, while the upper one cooled down until it reached zero. Both these experiments prove that water is heavier at 4° than at 0°, for in both cases it sinks to the lower part of the vessel. This experiment may be adapted for lecture illustration by using a cylinder containing water at 15° C., with its central part surrounded by a jacket containing bruised ice (fig. 261).

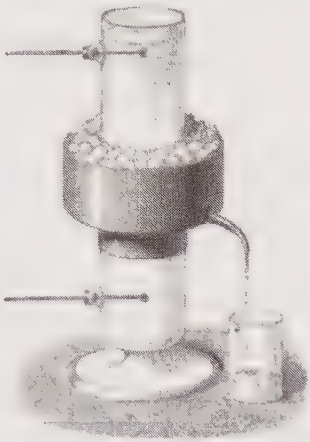


Fig. 261.

This may also be illustrated in a simple and interesting manner by means of a *specific gravity bulb* (fig. 262), which in this case is so adjusted that it exactly floats in water of about 3° C. Such a bulb will sink if placed in a vessel containing water at 0°; but when that water is placed in a warm room its temperature gradually rises, and when it is about 3° the bulb rises to the top of the liquid; the temperature continuing to rise, when it is at about 9° the bulb again sinks to the bottom.

Fig. 262.

The phenomenon of the maximum density of water is of great importance in the economy of nature. In winter the temperature of lakes and rivers falls, from being in contact with the cold air, and from other causes, such as radiation. The colder water sinks to the bottom, and a continual succession of currents is formed, until the whole has a temperature of 4°. The cooling

on the surface still continues, but the cooled layers, being lighter, remain on the surface, and ultimately freeze, the water below the ice increasing in temperature from 0° to 4°. The ice thus formed protects the water below, the bulk of which remains at a temperature of 4°, even in the most severe winters, a temperature at which fish and other inhabitants of the water are not destroyed.

EXPANSION OF GASES

245. **Value of the coefficient of expansion of gases.**—Not merely are gases the most expansible of all bodies, but their expansion is the most regular. It was originally assumed, on the basis of Gay-Lussac's experiments, that all gases expanded to the same extent for the same increase of temperature—that is, that they had all the same coefficient of expansion. It has, however, been established that the coefficients of various gases do present slight differences. They are, however, so slight that for ordinary practical purposes they may be assumed to be the same—that is to say, ·00367, or 367 parts in 100,000 ; or, in other words, 100,000 volumes of air, or any other gas, when heated from 0° to 1° Centigrade, would become 100,367 volumes, or 273 volumes would become 274. This expansibility is about 9 times as great as that of water.

246. **Effects of the expansion of gases.**—The expansion of gases affords us numerous important applications, not merely in domestic economy, but also in atmospheric phenomena. Thus in our dwellings, when the air is heated and vitiated by the presence of a great number of persons, it expands and rises, in virtue of its diminished density, to the highest parts of rooms ; and, to allow this to escape, apertures are made in the cornice, while fresh and pure air enters by the joints of the doors and of the windows.

Fig. 263.

When, in winter, the door of a warm room is put ajar, and a lighted candle held near the top, c (fig. 263), the direction of the flame proves the existence of a current of warm air from the inside to the outside. If we lower the flame, it will be found that at about the middle, b, it is not affected by any air-current, but that lower down, near the ground, a, the flame is driven inwards.

In theatres the spectators in the galleries are exposed to the

highest temperature and the most impure air, while those near the orchestra breathe in a purer air.

Draughts in chimneys are due to the expansion of air. Heated by the fire in the grate, the air rises in the chimney with a velocity which is greater the more it is expanded. Hence results a rapid current of air, which supports and quickens the combustion by constantly replacing the oxygen absorbed. This draught is stronger the colder the outer air, the stronger the fire, and the taller the column of hot air—that is, the higher the chimney.

The expansion and contraction of air have a fortunate influence on the temperature of that part of the atmosphere in which we live. For when the ground is strongly heated by the sun's burning rays, the layers of air in immediate contact with it tend to acquire the same temperature and to form a stifling atmosphere : but these layers, gradually expanding, rise from their lessened density ; while the higher layers, which are colder and denser, gradually replace them. The high temperature which would otherwise be produced in the lower regions is thereby moderated, and is thus kept within the limits which plants and animals can support.

The expansion and contraction produced in the atmosphere over a large tract of country are the cause of all winds, from the lightest zephyr to the most violent hurricane. These winds, which at times are so destructive, so capricious in their direction, and so variable in their strength, not merely have the effect of mixing the heated and the cooler part of the atmosphere, and of thus moderating extremes of temperature, but by driving away the vitiated atmosphere of our towns, and replacing it by pure air, they are one of the principal causes of salubrity ; without them our cities would be the centres of infection, where epidemic diseases of all kinds would be permanent. Without winds, clouds would remain motionless over the country where they were formed, neither rivers nor brooks would moisten the soil, and the greater part of the globe would be condemned to absolute dryness. But, carried by the winds, the clouds formed above the seas are transported to the centres of continents, where they condense and fall as rain ; and this, having fertilised the soil, gives rise to the numerous rivers which fall into the ocean, thereby establishing a continuous circulation from the seas towards the continents, and from continents towards seas.

247. **Density of gases.**—The specific gravities of solids and of liquids have been determined in reference to water (111) ; those of

gases by comparison with air—that is, having taken as a term of comparison, or *unity*, the weight of a certain volume of air, the weights of the same volume of other gases are determined. But as gases are very compressible and expansible, and as, therefore, their specific gravities may greatly vary, they must be reduced to a definite pressure and temperature. This is why *the temperature of zero* and *the pressure of* 30 *inches* have been chosen.

Hence the *relative density* of a gas, or its *specific gravity*, is the relation of the weight of a certain volume of the gas to that of the same volume of air; both the gas and the air being at zero, and under a pressure of 30 inches.

In order, therefore, to find the specific gravity of a gas—oxygen, for instance—it is necessary to determine the weight of a certain volume of this gas, at a pressure of 30 inches and a temperature of zero, and then the weight of the same volume of air under the same conditions. For this purpose a large globe of about two gallons capacity is used, like that represented in fig. 117, the neck of which is provided with a stopcock, which can be screwed to the air-pump. The globe is first weighed empty, and then full of air, and afterwards full of the gas in question. The weights of the gas and of the air are obtained by subtracting the weight of the exhausted globe from the weights of the globe filled, respectively, with air and gas. The quotient obtained by dividing the latter by the former gives the specific gravity of the gas. It is difficult to make these determinations at the same temperature and pressure, and therefore all the weights are reduced by calculation to zero, and the standard pressure of 30 inches.

In this manner the following densities have been found:—

Air	1·0000	Nitrogen	0·9714
Hydrogen	0·0692	Oxygen	1·1056
Marsh gas	0·5590	Carbonic acid	1·5290
Ammonia	0·5887	Sulphurous acid	2·2474
Carbonic oxide	0·9670	Chlorine	2·4400

It appears from these numbers that the lightest of gases, and therefore of all bodies, is hydrogen, whose density is less than $\frac{1}{14}$ that of air.

CHAPTER VI

CHANGES OF STATE OF BODIES BY THE ACTION OF HEAT

248. **Fusion.**—In treating of the general effects of heat, we have seen that its action is not only to expand bodies, but to cause them to pass from the solid to the liquid state, or from the latter state to the former, according as the temperature rises or falls; and from the liquid to the aëriform state, or conversely. These various changes of state we shall now investigate under the name of *fusion or melting*, *solidification*, *vaporisation*, and *liquefaction*.

Fusion, or melting, is the passage of a solid body to the liquid state by the action of heat. This phenomenon is produced when the force of cohesion which unites the molecules is sufficiently weakened; but as the cohesive force varies in different substances, the temperature at which bodies melt does so likewise. For some substances this temperature is very low, and for others very high, as the following table shows:—

Melting-points of certain substances

Mercury	−38·8°	Bismuth	269°
Bromine	−12	Cadmium	321
Ice	0	Lead	328
Rape oil	+1	Zinc	419
Butter	+33	Antimony	450
Phosphorus	44	Aluminium	655
Potassium	55	Silver	955
Stearine	60	Gold	1060
White wax	65	Iron—cast	1150
Sodium	90	„ wrought	1600
Sulphur	114	Platinum	1775
Tin	232	Iridium	1950

Some substances, however, such as paper, wood, wool, and certain salts, do not fuse at a high temperature, but are decomposed. Many bodies have long been considered *refractory*—that is,

incapable of fusion ; but, in the degree in which it has been possible to produce higher temperatures, their number has diminished. Gaudin succeeded in fusing rock crystal by means of a lamp fed by a jet of oxygen ; and Despretz, by combining the effects of the sun, the voltaic battery, and the oxyhydrogen blowpipe, melted alumina and magnesia, and softened carbon so that it was flexible, which is a condition near that of fusion. By means of the electric furnace, alumina and other earths are readily brought to the liquid condition.

Some substances pass from the solid to the liquid state without showing any definite melting-point—for example, glass and iron become gradually softer and softer when heated, and pass by imperceptible stages from the solid to the liquid condition. This intermediate condition is spoken of as the state of *vitreous fusion.* Such substances may be said to begin to melt at the lowest temperature at which perceptible softening occurs, and to be fully melted when the further elevation of temperature does not make them more fluid ; but only approximate temperatures can be given as those of their true melting-points.

Fig. 264.

The determination of the melting point of a body is a matter of considerable importance in fixing the identity of many chemical compounds, and is, moreover, an operation frequently necessary in determining the commercial value of tallow and other fats.

In the case of a substance like tallow, the operation is as follows : A portion of the substance is melted in a watch-glass, and a small quantity of it sucked into a fine capillary tube, which is then placed in a bath of clear water (fig. 264) attached to a thermometer, and the temperature of the bath is gradually raised until the substance ceases to be opaque, that is, is completely melted, and the temperature at which this occurs is noted. The bath is then

allowed to cool, and the solidifying-point noted, and the mean of the two is taken as the true melting-point.

249. **Laws of fusion.**—It has been found by experiment that the fusion or melting of bodies is governed by the two following laws :—

I. *Every substance begins to fuse at a certain temperature, which is invariable for one and the same substance if the pressure be constant.*

II. *Whatever be the temperature of the source of heat, from the moment fusion commences the temperature of the body ceases to rise, and remains constant until the fusion is complete.*

For instance, the melting-point of ice is zero, and a piece of this substance exposed to the sun's rays, or placed in front of a fire or over a lamp, could never be heated beyond this temperature. Exposure to a stronger heat would only hasten the fusion : the temperature would remain at zero until the whole of the ice was melted.

Alloys are generally more fusible than any of the metals of which they are composed—for instance, an alloy of 5 parts of tin and 1 of lead fuses at 194°. The alloy known as *Rose's fusible metal*, which consists of 4 parts of bismuth, 1 part of lead, and 1 of tin, melts at 94° ; and an alloy of 1 or 2 parts of cadmium with 2 parts of tin, 4 parts of lead, and 7 or 8 parts of bismuth, known as *Wood's fusible metal*, melts between 66° and 71° C. Fusible alloys are of extended use in soldering and in taking casts.

A mixture of the chlorides of potassium and of sodium fuses at a lower temperature than either of its constituents ; the same is the case with a mixture of the carbonates of potassium and sodium, especially when they are mixed in the proportion of their chemical equivalents.

An important application of this property is met with in the case of *fluxes*, which are much used in metallurgical operations. They consist of substances which, when added to an ore, partly, by their chemical action, help the reduction of the substance to the metallic state, and partly, by presenting a readily fusible medium, hasten the agglomeration of the particles, and thus promote the formation of a *regulus* or mass of pure metal.

250. **Latent heat.**—Since, during the passage of a body from the solid to the liquid state, the temperature remains constant until the fusion is complete, whatever be the intensity of the source of heat, it must be concluded that in changing their condition, bodies

absorb a considerable amount of heat, the only effect of which is to maintain them in the liquid state. This heat, which is not indicated by the thermometer, is called *latent heat* or *latent heat of fusion*, an expression which, though not in strict accordance with modern ideas, is convenient from the fact of its universal recognition and employment.

An idea of what is meant by latent heat may be obtained from the following experiment. If a pound of water at 80° is mixed with a pound of *water* at zero, the temperature of the mixture is 40°. But if a pound of *ice* at zero is mixed with a pound of water at 80°, the ice melts, and two pounds of water at *zero* are obtained. The pound of ice at zero is changed into a pound of water also at zero; but as the hot water is also lowered to this temperature, what has become of the 80 units of heat it possessed? They exist in the water which results from the ice; their effect has been to increase neither its temperature nor its volume, but simply to impart fluidity to it. Consequently, the mere change of a pound of ice to a pound of water at the same temperature requires as much heat as will raise a pound of water through 80°. This quantity of heat represents the *latent heat of the fusion of ice*, or the *latent heat of water*. The term *unit of heat* employed above means the quantity of heat required to raise the temperature of a pound of water by 1°, or the heat given up by a pound of water in cooling through 1°.

Every substance in melting absorbs a certain amount of heat, which, however, varies materially with different substances. Thus the latent heat of fusion for phosphorus is 5, for sulphur 9, and for sodium nitrate 63; that is, as much heat is required to melt a pound of this salt at its melting point as would raise 63 pounds of water through 1°.

The enormous quantity of heat absorbed by ice and snow in melting explains how it is that so long a time is required to melt them when thaw sets in. And, conversely, it is owing to the latent heat of water that, even when its temperature has been reduced to zero, so long a time is required before it is entirely frozen.

Were it not for the great amount of heat which must be absorbed by snow or ice in melting, we should, on a change from frost to mild weather, be liable to the most destructive floods owing to the sudden melting of the accumulated snow and ice.

251. **Solidification.**—Those substances which are liquefied by

heat revert to the solid state on cooling, and this passage from the liquid to the solid state is called *solidification.*

In all cases the phenomenon is subject to the two following laws :—

I. *Every substance under the same pressure solidifies at a fixed temperature which is the same as that of fusion.*

II. *From the commencement to the end of the solidification, the temperature of the substance remains constant.*

Thus, if lead begins to melt at 328°, melted lead, in like manner, when cooled down, begins to solidify at 328°. Moreover, until it is completely solidified, the temperature remains constant at 335°. This arises from the fact that the liquid metal, in proportion as it solidifies, restores the heat it had absorbed in being melted. The same phenomenon is observed whenever a liquid solidifies.

Pure water freezes at zero; olive and rape oils at $-6°$; linseed and nut oils at $-27°$; bisulphide of carbon at $-116°$; ether and alcohol at about $-130°$.

If water contains salts or other foreign bodies, its freezing-point is lowered. Sea water freezes at $-2·5°$ to $-3°$ C.; the ice which forms is quite pure, and a saturated solution remains. In Finland advantage is taken of this property to concentrate sea water for the purpose of extracting salt from it. If water contains alcohol, precisely analogous phenomena are observed; the ice formed is pure, and, practically, all the alcohol is contained in the residue.

If kept quite still, water may be cooled below zero without solidifying. A drop of water on a surface which it does not moisten, such as velvet, may be thus cooled, but when touched by the point of a pin it at once freezes.

Water presents the remarkable phenomenon that when it solidifies and forms ice its volume undergoes a material increase. In speaking of the maximum density of water we have already seen that, on cooling, it expands from 4 degrees to zero; it further expands at the moment of solidifying, or contracts on melting by about 10 per cent. One volume of ice at 0° gives 0·908 of water at 0°, or 1 volume of water at 0° gives 1·102 of ice at the same temperature.

The increase of volume in the formation of ice is accompanied by an expansive force which sometimes produces powerful mechanical effects, of which the bursting of waterpipes and the breaking of jugs and bottles containing water are familiar examples. The

splitting of stones and rocks and the swelling up of moist ground during frost are caused by the fact that water penetrates into the pores and there becomes frozen. The bursting of water-pipes takes place during actual frost, but the solid ice usually closes the crack and prevents any escape of water, and the ill effects only show themselves when the thaw has set in and the ice is melted.

The expansive force of ice was strikingly shown by some experiments of Major Williams in Canada. Having quite filled a 13-inch iron bomb-shell with water, he firmly closed the touch-hole with an iron plug weighing 3 pounds, and exposed it in this state to the frost. After some time the iron plug was forced out with a loud explosion, and thrown to a distance of 415 feet, the shell was cracked, and a mass of ice projected from the crack, as shown in fig. 265.

Fig. 265.

From the expansion which water undergoes in freezing, it is obvious that ice must be less dense than water; and this, in fact, is the case, for ice floats on the surface of the water. In the polar seas, where the temperature is always very low, masses of floating ice are met with which are called *ice-fields*. They rise out of the sea to a height of as much as 4 or 5 yards, and are immersed to a depth of at least eleven times as much, and they frequently extend over an area of 40 miles. True mountains of ice, or *icebergs*, are found floating on those seas; they have not the same area, but attain very great heights. One measured in Melville Bay was 315 feet in height, and three-quarters of a mile in length. They are not produced on the sea, but are the tails of glaciers formed on the land, and broken off as the glacier descends towards the sea.

Cast iron, bismuth, and antimony expand on solidifying, like water, and can thus be used for casting; but gold, silver, and copper contract, and hence coins of these metals cannot be cast, but must be stamped with a die.

252. **Crystallisation.**—When bodies pass slowly from the liquid to the solid state, their molecules, instead of becoming grouped in a confused manner, generally acquire a regular order and arrangement, in virtue of which these bodies assume the geometrical shapes of cubes, pyramids, and prisms, etc., which are perfectly definite, and are known as *crystals*. Flakes of snow, when looked at under the microscope (305), ice in the process of formation,

sugar candy, rock crystal, alum, nitre, common salt, and many other substances, afford well-known instances of crystallisation.

Two methods are in use for crystallising substances: the *dry way* and the *moist way*. By the first method bodies are melted by heat and then allowed to cool slowly. The vessel in which the operation is performed becomes lined with crystals, which are made apparent by inverting the vessel and pouring out the excess of liquid before the whole of it is solidified. Sulphur, bismuth, and many other metals are thus easily crystallised. The second method consists in dissolving in hot water the substance to be crystallised, so as to form a saturated solution (253), which is then allowed to cool

Fig. 266.

slowly. The body is thereby deposited on the sides of vessels in crystals, which are larger and better shaped the more slowly the crystallisation is effected. In this manner sugar candy and salts are crystallised. Fig. 266 represents a mass of crystals of alum obtained in this way.

253. **Solution.**—A body is said to *dissolve* when it becomes liquid in consequence of an attraction between its molecules and those of a liquid in which it is placed and which is thus called its *solvent*. Gum arabic, sugar, and most salts dissolve in water. Beeswax does not dissolve in water, but does so in turpentine. The weight that can be dissolved generally increases with the

temperature, as is seen from the following table, which gives the solubilities of the salts dissolved for the temperatures given :—

Temperature	Common Salt	Nitre	Potassium Chloride	Copper Sulphate	Zinc Sulphate
0°	35	13	29	32	115
20°	37	21	35	42	161
100°	39	247	56	203	654

When a liquid has dissolved as much as it can at a particular temperature, it is said to be *saturatea.*

During solution, as well as during fusion, a certain quantity of heat always becomes latent, and hence it is that the solution of a substance usually produces a diminution of temperature. In certain cases, however, instead of the temperature being lowered, it actually rises, as when caustic potash is dissolved in water. This depends upon the fact that during the solution of a solid in a liquid two simultaneous and contrary phenomena are occurring. The first is the passage from the solid to the liquid condition, which always lowers the temperature. The second is the *chemical* combination of the body dissolved with the liquid, which, as in the case of all chemical combinations, produces an increase of temperature. Consequently, as the one or the other of these effects predominates, or as they are equal, the temperature either rises or sinks, or remains constant.

254. **Freezing mixtures.**—The absorption of heat in the passage of bodies from the solid to the liquid state has been used to produce artificial cold. This is effected by mixing together bodies which have an affinity for each other, and of which one at least is solid, such as water and a salt, ice and a salt, or an acid and a salt. Chemical affinity accelerates the fusion ; the portion which melts robs the rest of the mixture of a large quantity of sensible heat, which thus becomes latent. In many cases a very considerable diminution of temperature is produced.

If the substances taken be themselves first previously cooled down, a still more considerable diminution of temperature is occasioned.

Freezing mixtures are frequently used in chemistry, in physics, and in domestic economy. The best effect is obtained when pretty large quantities, 2 or 3 pounds, of the mixture are used, and when they are intimately mixed.

One form of the portable ice-making machines which have come into use of late years is represented in fig. 267. In this ice is made by the great cold produced by the solution of ammonium nitrate in water. In a metal cylinder, A, a hollow cone, B, of thin metal plate is so fixed as to divide the interior of A into two parts: the cone B open at the top, and the ring-shaped space P surrounding it, and open at the bottom. The water to be frozen is placed in B to about $\frac{1}{8}$ its height; an india rubber ring is placed on it, and then a wooden cover which can be screwed tightly down. B being thus closed, the space P is about half filled with ammonium nitrate, and water added until the space is nearly full. P having been closed by a cover similar to that of B, the whole apparatus is rotated for 8 or 10 minutes on its axis. There is then formed in B a hollow cone of transparent ice, in the centre of which there is usually some water. Instead of placing water in B, mixtures of suitably flavoured creams and the like may be placed, and are frozen with equal facility.

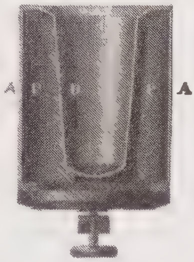


Fig. 267.

The salt can be obtained again by evaporating the solution, and thus the process can be repeated over and over again with the same materials.

A mixture of sodium sulphate or Glauber's salt and hydrochloric acid produces also a great degree of cold; but, as a chemical decomposition takes place here, the mixture can only be used once. The greatest lowering of temperature is produced by taking two solids which by their mixture produce a liquid. Thus, a mixture of 1 pound of common salt with 3 pounds of snow or coarsely powdered ice reduces the temperature to $-20°$ C.

One of the most useful materials for freezing mixtures is crystallised calcium chloride; when this is mixed with snow in the proportion of 10 parts of salt to 7 parts of snow, a temperature of $-42°$ C. is obtainable. By heating the solution thereby produced, and evaporating until the temperature reaches 129°, and then allowing it to cool, stirring all the time, the salt is reproduced in the solid form in the state of a fine crystalline meal, which can be used again for fresh operations.

CHAPTER VII

FORMATION OF VAPOURS. MEASUREMENT OF THEIR ELASTIC FORCE

255. **Vapour.**—We have already seen (118) that *vapours* are the aëriform fluids into which liquids such as ether, alcohol, water, and mercury are changed by the action of heat.

As regards the property of disengaging vapour, liquids are divided into two classes—*volatile* liquids and *fixed* liquids. The first are those which have a tendency to pass into the state of vapour at the ordinary or even at lower temperatures ; such, for instance, are water, ether, chloroform, and alcohol, which disappear more or less rapidly when exposed to the air in open vessels. To this class belongs a numerous family of liquids met with in nature, such as essence of turpentine, oil of lemons, of lavender, of thyme, of roses, etc., which are known as the *essential oils*.

Fixed liquids, on the contrary, are those which emit no vapour at any temperature ; such, for instance, are the *fatty oils*, as olive, rape, etc. When strongly heated, these oils are decomposed, and give rise to gaseous products ; but they do not emit vapours of the same nature as their own. There are some of them which are known as *drying oils*, that become thicker in the air ; but this is in consequence of their having absorbed oxygen, and so undergone a chemical change, and not in consequence of evaporation.

Some substances, even in the solid state, form vapour. Ice is an instance of this, as is seen in dry cold winters, where the snow and ice quite disappear from the ground, without there having been any melting. Iodine, camphor, odoriferous solids in general, and the positive carbon in the electric arc (511), present the same phenomenon. Bodies which by the action of heat pass directly from the solid state to that of vapour are said to *sublime*, and this process is called *sublimation*.

The vapours of most colourless liquids are colourless also, and therefore invisible. What, in ordinary life, we speak of as steam

or vapour—the breath from our mouths in winter, the cloud over boiling water, and the like—is no longer steam or vapour, but is vapour which has been condensed into small spherules of liquid, and which then remains suspended in the air, but afterwards disappears, forming invisible water gas.

256. **Elastic force of vapour.**—Vapours formed on the surface of a liquid are disengaged in virtue of their elastic force ; but this pressure is generally far lower than that of the atmosphere, and hence liquids exposed to the air only evaporate slowly.

The following experiment renders evident the elastic force or pressure of vàpour. A bent glass tube has the shorter limb closed (fig. 268) ; this branch and part of the longer are filled with mercury. A drop of ether is then passed into the closed leg, which, in virtue of its lower density, rises to the top of the tube at B. The tube thus arranged is immersed in a vessel of water at a temperature of about 45°. The mercury then sinks slowly in the short branch, and the space AB is filled, with the exception of a small quantity of liquid ether at A, with a gas which has all the appearance of air. This gas or aëriform fluid is nothing but the vapour of ether, whose elastic force counterbalances not only the pressure of the column of mercury, CA, but also the atmospheric pressure exerted at C.

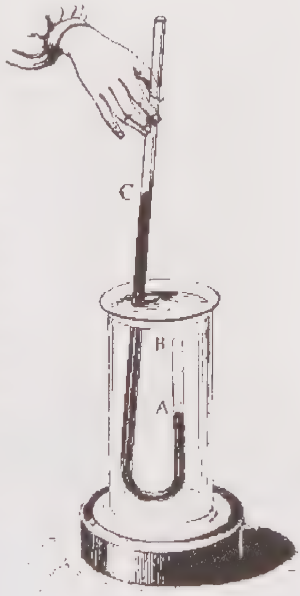


Fig. 268.

If the water in the vessel be cooled, or if the tube be withdrawn, the mercury gradually rises in the short leg, and the liquid ether which seemed almost to have disappeared increases. If, on the contrary, the water in which the tube is immersed be still more heated, the drop diminishes and the mercury sinks further in the short leg ; thus showing that fresh vapours are formed, and that the elastic force increases. This

increase of pressure with the temperature continues as long as any liquid remains to be vaporised.

The crackling of wood in fires is due to the increased pressure of the vapours and gases formed in the pores of the wood during combustion. In roasting chestnuts it is usual to slit the outer skin, so as to allow the vapour formed to escape, for otherwise it might acquire such an elastic force as to burst the chestnut and scatter the particles far and wide.

257. **Formation of a vapour in a vacuum.**—In the previous experiment the liquid changed very slowly into the state of vapour; this is also the case when a liquid is freely exposed to the air. In both cases the atmosphere is an obstacle to the vaporisation. In a vacuum there is no resistance, and the formation of vapours is instantaneous, as is seen in the following experiment. Four barometer tubes, filled with mercury, are immersed side by side in the same trough (fig. 269). One of them, A, serves as a barometer—that is, only contains dry mercury—and a few drops of water, alcohol, and ether are respectively introduced into the tubes B, C, D. When the liquids reach the vacuum a depression of the mercury is at once produced. But this depression cannot be produced by the weight of a liquid, for it is but a very small fraction of the weight of the displaced mercury. Hence, in the case of each liquid, some vapour must have been formed whose elastic force has depressed the mercurial column, and as the depression is greater in the tube D than in the tube C, and greater in this than in the tube B, it is concluded that, for the

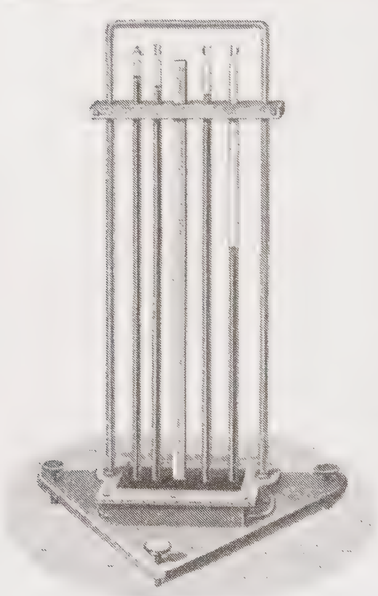


Fig. 269.

same temperature, the elastic force of ether is greater than that of alcohol vapour, and that this in turn has a greater elastic force than water vapour. If the depression be measured by means of a graduated scale, it will be found that, at a temperature of 20°, the elastic force of ether is twenty-five times as great as that of water, and that of alcohol almost four times as great. From these experiments we conclude that :—

I. *In a vacuum all volatile liquids are at once converted into vapour.*

II. *At the same temperature the vapours of different liquids have different elastic forces.*

When petroleum is gradually raised in temperature by being placed on a water bath, a point is reached at which the vapour ignites when a light is brought over the liquid. This is called the *flash-point* ; its determination is a matter of great practical importance. Most of the accidents due to petroleum are caused by oils of low flash-point. The lowest limit at present is 73° F. ; it is considered that if the flash-point were raised to 100° F. fires resulting from accidents with petroleum lamps would practically cease.

258. **Limit to the formation and to the pressure of vapour. Saturated space.**—The quantity of vapour which can be formed in a given space, whether at the ordinary or at higher temperatures, is always limited—for instance, in the above experiment, the depression of mercury in each tube, B, C, D (fig. 269), is not stopped for want of liquid which might form fresh vapour, for care is taken always to add so much that a slight excess remains unvaporised. Thus, in the tube D, enough ether is left ; yet we might wait weeks and years, and if the temperature did not increase, we should always see a portion of liquid in the tube, and the level of the mercury remain stationary. This shows that no new vapour can be formed in the tube, and at the same time that the elastic force of the vapour which is there cannot increase, which is expressed by saying that it has attained its *maximum pressure.*

When a given space has acquired all the vapour which it can contain at a fixed temperature, it is said to be *saturated.* For instance, if in a bottle full of dry air a little water be placed, and the vessel be hermetically closed, part of the water will evaporate slowly, until the elastic force of the vapour formed holds in equilibrium the expansive force of that which still tends to form ; the formation of vapour then ceases, and the space is saturated.

259. **The quantity of vapour which saturates a given space is**

the same whether this is vacuous or contains air.—For the same temperature the quantity of vapour necessary to saturate a given space is proportional to the pressure, and is the same whether the space is quite vacuous or contains air or any other gas. This may be shown by the experiment represented in fig. 270. A is a stout bottle which has been filled with dry air; it is connected by means of a flexible india rubber tube with a mercury manometer. In A is a thin glass bulb containing water or any other volatile liquid. When this is broken by shaking A, the liquid volatilises, and by its elastic force depresses the mercurial column. If the position of this column be read off before and after the experiment, the difference measures the vapour-pressure of the liquid, and this is found to be the same as if the experiment had been made with the same liquid with the apparatus of fig. 269, provided the temperature be the same. The difference between evaporation in air and in a vacuum is that in the former case the evaporation only takes place slowly, while in the second case it is instantaneous. Yet, for the same space, whether it be vacuous or full of air, the quantity of vapour formed which corresponds to the state of saturation varies with the temperature. The higher the temperature, the greater is the quantity of vapour; on the other hand, the lower the temperature, the less is the quantity required to saturate a given space.

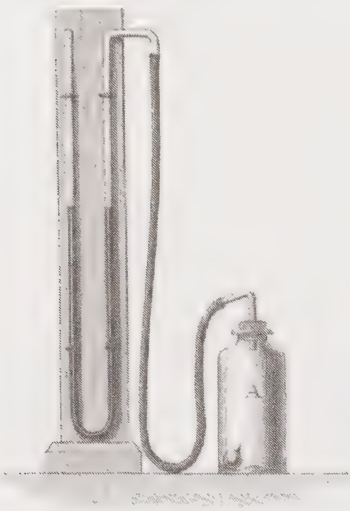


Fig. 270.

The quantity of vapour present in atmospheric air is very variable; but, spite of the abundant vaporisation produced on the surface of seas, lakes, and rivers, the air in the lower regions of the atmosphere is seldom quite saturated, even when it rains. This arises from the fact that aqueous vapour, being less dense than air, rises into the higher regions of the atmosphere, in pro-

portion as it is ormed, where, condensed by cooling, it falls as rain. During a dense fog the air is quite saturated.

260. **Evaporation. Causes which accelerate it.**—We have hitherto described under the general term of *vaporisation* all production of vapour, under whatever circumstances it takes place, whether slow or rapid, whether in air or in a vacuum ; while the term *evaporation* is especially assigned to the slow formation of vapour on the surface of a volatile liquid when it is exposed in the open air. It is in consequence of evaporation that the level of the water in a pond in dry weather gradually sinks, and the pond ultimately dries up if it is not fed by a spring. Owing to the same cause the moist earth dries up and hardens in fine weather, and wet linen exposed in the air soon becomes dry. Several causes influence the rapidity of the evaporation of a liquid : its temperature, the quantity of the same vapour in the surrounding atmosphere, the renewal of this atmosphere, also the extent of the surface of the liquid.

Influence of temperature. The higher the temperature, the more abundant is the formation of vapour. This property is utilised in daily life to hasten and complete the drying of a large number of products which are exposed in *stoves*—that is to say, in chambers the temperature of which is kept at 30, 40, 60, and even 100 degrees, and the air of which is continually renewed to allow the vapour formed to escape.

Fig. 271.

Influence of pressure. We have already seen that the pressure of the atmosphere is an obstacle to the disengagement of vapour, and it will thus be understood that when this pressure is diminished vapour ought to be formed more abundantly. This, in point of fact, is what takes place whenever liquids are under a lower pressure than that of the atmosphere. In sugar refineries, in order to concentrate the syrups, that is, to reduce the volume by removing part of the water they contain, they are placed in large spherical boilers ; and then, by the aid of large air-pumps of special construction, worked by steam-engines, the air in the boilers is rarefied, which considerably accelerates the evaporation of water, and quickly brings the syrups to the wished-for degree of concentration.

The rate at which water evaporates in the air may be investigated by means of the *evaporometer* (fig. 271), which consists

of a graduated glass tube, *a*, nine inches long, $\frac{5}{8}$ inch in diameter, and closed at one end. It is filled with water, and closed at the bottom by a disc, *o*, of thick blotting-paper; this is kept in its place by a brass ring, which is pressed by a spring passing round the tube. The area of the disc is known, and, by observing the extent to which the level of the water has sunk during a certain interval of time, we have at once the means of calculating the volume of water which has evaporated during this time. The instrument is suspended in the open air in the shade, and near it is a wet-bulb thermometer. At London the amount of water which evaporates in a year is represented by the height of a column of water of two feet.

Influence of the renewal of air. In order to understand the influence of the third cause, it is to be observed that no evaporation of a liquid takes place in a space already saturated with the vapour of that liquid, and that evaporation reaches its maximum in air completely freed from this vapour. It therefore follows that, between these two extremes, the rapidity of evaporation varies according as the surrounding atmosphere is already more or less charged with the same vapour.

The effects of the renewal of this atmosphere are easily explained; for if the air or gas which surrounds the liquid is not renewed, it soon becomes saturated, and evaporation ceases. Thus it is that the wind, removing the layers of air which are in contact with the earth, soon dries up the roads and streets. Hence, too, it is that linen hung out to dry does so far more rapidly on a windy than on a calm day.

Influence of the extent of surface. The greater the extent of surface which a liquid presents to the air, the more numerous are the points from which vapour is disengaged. Hence the evaporation of a liquid should be effected in vessels which are wide and shallow. This is what is done in the process of extracting salt from sea-water in *salt-gardens*. The sea-water is admitted into broad and shallow pits excavated in the ground. Under the influence of the sun's heat the water evaporates, and when the concentration has reached the point at which the liquid is saturated, the salt begins to form on the surface and is raked off.

261. **Ebullition.**—*Ebullition*, or *boiling*, is the rapid production of elastic bubbles of vapour within the mass of a liquid itself.

When the lower part of a vessel containing water is heated,

the first bubbles are due to the disengagement of air which had previously been absorbed. Small bubbles of vapour then begin to rise from the heated parts of the sides, but as they pass through the upper layers, the temperature of which is lower, they condense before reaching the surface. The formation and successive condensation of these first bubbles occasion the *singing* noticed in liquids before they begin to boil. Lastly, large bubbles rise through the liquid and burst on the surface, and this constitutes the phenomenon of ebullition (fig. 272).

262. **Laws of ebullition.**—The laws of ebullition have been determined experimentally, and are as follows :—

I. *The temperature of ebullition, or the boiling-point, increases with the pressure.*

II. *For a given pressure, boiling commences at a certain temperature, which varies in different liquids, but which for equal pressures is always the same in the same liquid.*

III. *Whatever be the temperature of the source of heat, as soon as ebullition begins, the temperature of the liquid remains stationary.*

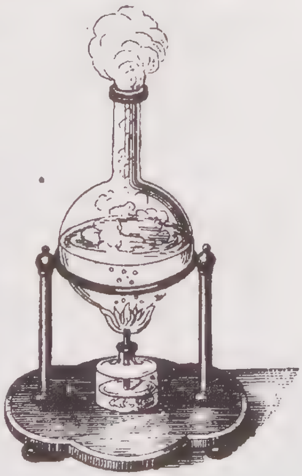


Fig. 272.

Thus, the boiling-point of water under the ordinary atmospheric pressure being 100°, water could not be heated beyond that point, whatever the temperature of the source of heat ; the only effect of higher temperature being to increase the rapidity of vaporisation ; hence all the heat which passes from the source into the liquid is absorbed by the vapour disengaged. But as the vapour is itself at 100°, we must conclude that this heat is not absorbed to raise the temperature of the vapour, but *simply to produce it*—that is, to change the substance from the liquid into the gaseous state—a phenomenon analogous to that which fusion presents (250). This disappearance of heat during ebullition will be subsequently investigated under the name of latent heat of vaporisation (267).

Boiling-points under the pressure of an atmosphere

Oxygen	$-182°$	Distilled water	$100°$
Carbonic acid	-80	Turpentine	157
Sulphurous acid	-10	Strong sulphuric acid	318
Ethylic chloride	$+11$	Mercury	357
Ether	37	Sulphur	444
Bisulphide of carbon	47	Cadmium	756
Bromine	58	Zinc	916
Alcohol	78	Lead	1450

263. **Causes which influence the boiling-point.**—The boiling-point of a liquid is affected by the presence of substances in solution, by the pressure to which it is subjected, and by the nature of the vessel in which the boiling takes place.

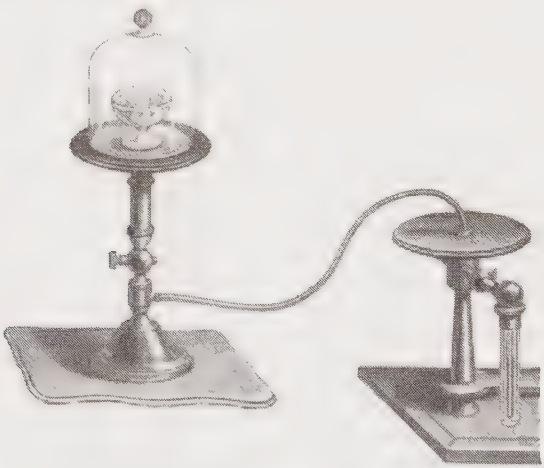


Fig. 273.

The boiling of a liquid is the more retarded the greater the quantity of any substance it may contain in solution, provided that the substance is not volatile, or, at all events, is less volatile than the liquid itself. Water, which boils at 100° when pure, boils at 109° when it is *saturated* with common salt—that is, when it has taken up as much of this salt as it can dissolve.

Influence of pressure. The pressure to which a liquid is

subjected has the most important influence on its boiling-point. The greater the external pressure, the greater must be the tension in order that the vapour may be disengaged, and therefore the higher the temperature. On the contrary, the less the pressure, the lower the temperature at which boiling takes place. If the pressure of the atmosphere be sufficiently diminished, water may be made to boil at the ordinary temperature. The experiment may be arranged in the manner represented in fig. 273. A glass cup containing water is placed under the bell-jar of an air-pump, or, in order that the experiment may be seen by a number of spectators, the bell is placed on a movable plate connected with the pump by a tube. When the air is very rarefied, the water is seen to boil, evidently indicating a considerable disengagement of vapour. Yet

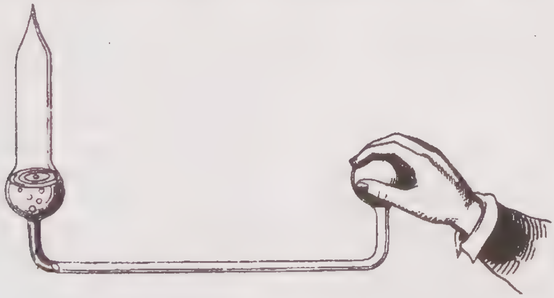


Fig. 274.

the temperature of the liquid is not raised; the boiling, on the contrary, lowers the temperature, owing to the heat which becomes latent in the formation of vapour.

The influence of pressure on boiling may further be illustrated by means of an experiment of Franklin's. The apparatus consists of two bulbs connected together by small glass tubing, one of which has a piece of wide tubing sealed to it (fig. 274). This is drawn out and the apparatus filled with water, which is then in great part boiled away by means of a spirit-lamp. When it has been boiled long enough to expel all the air, the tube is sealed as in the construction of the water-hammer (55). There is then a vacuum in the apparatus, or, rather, there is only a pressure due to the aqueous vapour, which at ordinary temperatures is very small. Consequently, if the bulb be placed in the hand

as shown in the figure, the heat is sufficient to produce a pressure, which drives the water into the tube and causes a brisk ebullition.

A paradoxical but very simple experiment also well illustrates the dependence of the boiling-point on the pressure. Water is boiled for some time in a glass flask, and when all air has been expelled by the steam the flask is closed by a cork and inverted, as shown in fig. 275. If the bottom is then cooled by a stream of cold water from a sponge, the water begins to boil again. This arises from the condensation of the steam above the surface of the water, by which a partial vacuum is produced.

Fig. 275.

As the pressure of air diminishes in proportion as we rise in the atmosphere, it will be seen, from what has been said, that on high mountains water must boil at lower temperatures than at the sea level. This, in fact, is the case. On Mont Blanc, at a height of 15,800 feet, water boils at 84°; at Quito, at a height of 11,000 feet, at 90°; on the St. Bernard at 92°; and at Madrid, the height of which is 3,000 feet, it boils at 97°. This diminution in the temperature of boiling at great heights is a material obstacle to the preparation of food, for at the temperature of 90° the extraction of the nourishment and of the flavour is far more imperfect than under the usual conditions.

In deep mines, on the contrary, such as those of Cornwall and of Lancashire, the reverse is the case; the pressure increases with the depth, and the boiling-point is raised above 100°.

Influence of the nature of the vessel on the boiling-point. Gay-Lussac observed that water in a glass vessel required a higher temperature for ebullition than in a metal one. Taking the tem-

perature of boiling water in a copper vessel at 100°, its boiling-point in a glass vessel was found to be 101°; and if the glass vessel had been previously cleaned by means of sulphuric acid and of potash, the temperature would rise to 105° or even 106° before ebullition commenced. Whatever be the boiling-point of water, the temperature of its vapour is uninfluenced by the material of the vessel in which the boiling takes place.

264. **Papin's digester.**—What has hitherto been said in reference to the formation of vapour has applied to the case of liquids heated in open vessels. Boiling can only take place under these conditions; for, in a closed vessel, since the vapour cannot escape into the atmosphere, its elastic force and density continually increase, but that peculiarly rapid disengagement of vapour which constitutes boiling is impossible. There is, moreover, this difference between heating in an open and in a closed vessel—that in the former case the temperature can never exceed that of ebullition, while in a closed vessel it may be raised, so to speak, to an indefinite extent. Thus we have seen (263) that in an open vessel water cannot be heated beyond 100° C., all the heat imparted to it being absorbed by the vapour disengaged. But as this disengagement of vapour cannot take place in a closed vessel, water and the vapour may be raised to a far higher temperature than 100°. This, however, is not unattended with danger, from the very high pressure which the vapour then acquires.

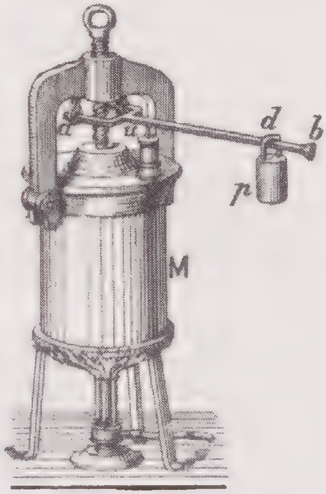


Fig. 276.

Fig. 276 represents the apparatus used in physical lectures for the purpose of heating water in a closed vessel beyond 100°. It is known as *Papin's digester*. It consists of a cylindrical metal vessel, M, provided with a cover, which is firmly fastened down by a screw. In order to close the vessel hermetically, sheet lead is placed between the edges of the cover and the vessel

In the cover there is a hole which is closed by a rod kept in place by a cylindrical guide, *u*. This rod presses against a lever, *ab*, movable at *a*, and the pressure may be regulated by means of a weight, *p*, movable on this lever. The lever is so weighted that when the pressure in the interior is equal to six atmospheres, for example, the valve rises and the vapour escapes. The destruction of the apparatus is thus avoided, and the mechanism, which will be described in speaking of the steam-engine (289), has hence received the name of *safety-valve*. The digester is filled about two-thirds with water, and is heated by a large Bunsen burner. The water may thus be raised to a temperature far above 100°, and the pressure of the vapour increased to several atmospheres according to the weight on the lever.

The apparatus has received the name of *digester*, from a Latin word signifying to dissolve, for the high temperature which water can acquire greatly increases its solvent power. Thus it is used to extract from bones the substance known as *glue*, which could not be accomplished at 100° C.

From the enormous pressure which vapour may acquire when heated in a closed vessel, it will be understood how important it is not to close tightly the vessel in which water is heated for domestic purposes. Thus a hot-water bottle for heating the feet of invalids should be uncorked before being placed near the fire ; for it might burst, or, at any rate, the cork might be driven out, and a more or less serious accident be caused. In like manner, when a locomotive stops, the steam must be allowed to escape ; for otherwise, as it is continually being formed in the boiler without any being consumed in working the engine, it might ultimately acquire such a pressure that an explosion would ensue.

265. **Measurement of the pressure of aqueous vapour.**—The important applications which have been made of the pressure of aqueous vapour have led philosophers to measure it accurately at various temperatures.

Dalton first measured the pressure of aqueous vapour for temperatures between 0° and 100° by means of the apparatus represented in fig. 277. Two barometer-tubes, A and B, are filled with mercury, and inverted in an iron bath full of mercury, and placed over a furnace or large Bunsen burner. The tube A is an ordinary barometer-tube ; but into the tube B is introduced a small quantity of water. The tubes are supported in a cylindrical vessel full of

water, the temperature of which is indicated by the thermometer, *t*. The bath being gradually heated, the water in the cylinder becomes heated too; the water which is in the tube, B, vaporises, and, in proportion as its vapour pressure increases, the mercury sinks. The depressions of the mercury corresponding to each degree of the thermometer are read off on the scale. Thus if, when the thermometer is at 70°, the mercury is 233 millimetres lower in the tube, B, than in the tube, A, it follows that at 70° the pressure of aqueous vapour is 233 millimetres, which is equivalent to 230 millimetres of mercury at 0° C., the standard temperature. This amounts to saying that the vapour exercises on the sides of the vessel which contains it a pressure equal to that due to a column of mercury 230 millimetres in height.

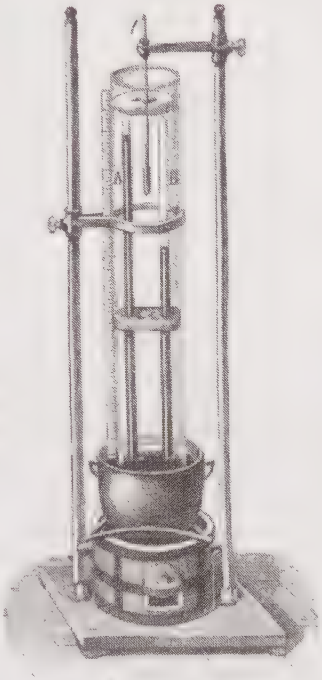


Fig. 277.

Dulong and Arago determined the pressure of aqueous vapour above 100° up to pressures of 24 atmospheres. More recently Regnault measured the pressure of aqueous vapour both above and below 100°. For temperatures below 100° he used two independent methods. Of these one was a modification of Dalton's; the other depends on the principle that when a liquid boils, the pressure of the vapour is equal to the pressure the liquid supports. If, therefore, the temperature and the corresponding pressure are known, the question is solved, and the method merely consists in causing water to boil under a given pressure and in measuring the corresponding temperature. The method is applicable to pressures greater than atmospheric.

The following table is due to Regnault.

Pressure of aqueous vapour from $-4°$ to $160°$ C.

Temperature	Pressure in millimetres of mercury	Temperature	Pressure in millimetres of mercury
$-4°$	3·39	30°	31·55
-2	3·96	40	54·91
0	4·60	50	91·98
1	4·94	60	148·79
2	5·30	65	186·95
3	5·69	70	233·09
5	6·53	75	288·52
10	9·17	80	354·64
12	10·46	90	525·45
13	11·06	100	760·00
15	12·70	101	787·63
17	14·42	120	1520·00
18	15·36	160	4580·00
20	17·39		

266. **Measurement of heights by the boiling-point.**—From the connection between the boiling-point of water and the pressure, the heights of mountains may be measured by the thermometer instead of by the barometer, since the pressure of the steam of boiling water is equal to that of the superincumbent atmosphere, whatever the temperature may be at which the water is boiling. Suppose, for example, it is found that water boils on the summit of a mountain at 90°, and at its base at 98° ; at these temperatures pressure of the vapour is equal to that of the pressure on the liquid—that is, to the pressure of the atmosphere at the two places respectively. Now, the pressure of aqueous vapour at various temperatures has been determined, and accordingly the pressures corresponding to the above temperatures are sought in the tables. These numbers represent the atmospheric pressures at the two places—in other words, they give the barometric heights—and from these the height of the mountain may be calculated by the method already given (140). An ascent of about 1,080 feet produces a lowering of 1° C. in the boiling-point, or, what is the same thing, an ascent of 600 feet produces a lowering of 1° F.

The instruments used for this purpose are called *thermobarometers* or *hypsometers*, and were first used by Wollaston. They consist essentially of a small metal vessel provided with a spirit-lamp for boiling water (fig. 278). To this is fitted a long tube,

the parts of which slide in each other like a telescope, so that it can be shut up for convenience in transport. By means of a cork a delicate thermometer fits in the top of the tube, so that the bulb and nearly the whole of the stem are surrounded by the steam. When the thread of mercury is stationary, its position is read off. The graduation of the thermometer is only from 80° or 90° to 100°; so that, each degree occupying a considerable space on the scale, the 10ths, and even the 100ths, of a degree may be estimated, and thus it is possible to determine the height of a place, by means of the boiling-point, to within about 10 feet.

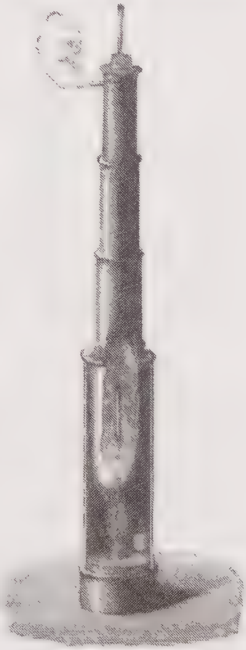


Fig. 278.

267. **Latent heat of vapour.**—In speaking of ebullition we have seen that, from the moment a liquid begins to boil, its temperature ceases to rise whatever be the intensity of the source of heat. It follows that a considerable quantity of heat becomes absorbed in ebullition, the only effect of which is to transform the body from the liquid to the gaseous condition. And, conversely, when a saturated vapour passes into the state of liquid, it gives out that amount of heat which it had absorbed in becoming converted into vapour.

This may be illustrated by means of the apparatus represented in fig. 279. The vessel *c* contains a certain weight of water at a known temperature, as indicated by a thermometer not shown in the figure; in the vessel, *a*, water is raised to the boiling-point, and when this is attained the open end of the pipe is dipped in *c*, and the boiling continued for some time. The increase in weight in *c* is then observed; this represents the weight of steam condensed, and the thermometer shows a rise of temperature. From these data the quantity of heat given out by the steam in condensing may be calculated. Thus, for instance, suppose the original weight of water in *c* to have been 1,000 grammes and its temperature 10°,

while at the end of the experiment it was 20°, and that the water distilled over and condensed weighed 16·3 grammes; then the quantity of heat which has been imparted to the cooling water has been 1,000 (20 – 10) = 1,000 × 10 = 10,000 thermal units (275), and this has been effected by the heat produced by the condensation of 16·3 grammes of steam at 100° to water at the same temperature, together with that which it has given out in cooling down to 20°. This latter is represented by the expression 16·3 $[x + (100-20)] = 16·3\ (x + 80)$, where x is the latent heat of vaporisation. By equating the two expressions the value of x is easily found; in this case it is 533.

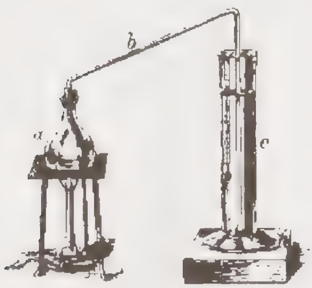


Fig. 279.

These phenomena were first observed by Black, who described them by saying that during vaporisation a quantity of sensible heat became latent, and that the latent heat again became free during condensation. The quantity of heat which a liquid must absorb in passing from the liquid to the gaseous state, and which it gives out in passing from the state of vapour to that of liquid, is spoken of as the *latent heat of vaporisation.*

The analogy of these phenomena to those of fusion will be at once seen. The modes of determining are described in principle in the above example; we may give the following results which have been obtained for the latent heats of vaporisation of a few liquids :—

Water	540	Bisulphide of carbon .	87
Alcohol	208	Turpentine	74
Ether	90	Bromine	46

The meaning of these numbers is—in the case of water, for instance—that it requires as much heat to convert a pound of water from the state of liquid, at the boiling-point, to that of vapour at the same temperature, as would raise a pound of water through 540 degrees, or 540 pounds of water through one degree Centigrade; or that the heat yielded by the conversion of one pound of vapour

of alcohol at 78° into liquid alcohol of the same temperature would raise 208 pounds of water through one degree.

It has been assumed that the boiling is under the ordinary pressure of the atmosphere; if the pressure is lower, and therefore the boiling-point lower, the value for the latent heat is greater. Watt supposed that the sum of the latent and sensible heats was a constant quantity, and equal to 640; thus, if water were boiled at 90°, its latent heat on this view would be 550. This is not, however, the case; Regnault showed that the *total heat of vaporisation*, $Q, = 606{\cdot}5 + 0{\cdot}305\,t$, where t is the temperature of boiling on the Centigrade scale.

268. **Cold due to evaporation.**—Whatever, then, be the temperature at which a vapour is produced, an absorption of heat always takes place. If, therefore, a liquid evaporates, and does not receive from without a quantity of heat equal to that which is expended in producing the vapour, its temperature sinks, and the cooling is greater in proportion as the evaporation is more rapid.

This may become a source of very great cooling. Thus, if a few drops of ether be placed on the hand, and this be agitated to accelerate the evaporation, great cold is experienced. By delivering the ether in the form of spray (fig. 175), the cold is still greater, and on this depends the method of obtaining local anæsthesia. With liquids which are less volatile than ether, like alcohol and water, the same phenomenon is produced, but the cooling is less marked.

On coming out of a bath, and more especially in the open air and with some wind, a very sharp cold is experienced, due to the evaporation of the water on the surface of the body. The wearing of moist linen is cold and dangerous, because it withdraws from the body the heat which the moisture requires for conversion into vapour.

The cooling effect produced by a wind or draught does not necessarily arise from the wind being cooler, for it may, as shown by the thermometer, be actually warmer than the surface of the skin, but arises from the rapid evaporation it causes. We have the feeling of oppression, even at moderate temperatures, when we are in an atmosphere saturated by moisture in which no evaporation takes place.

The cooling produced by the use of fans is due to the increased evaporation they produce. The freshness occasioned by watering the streets is also an effect of evaporation.

The fresh feeling experienced after a shower on a hot summer's day is due not only to the lower temperature of the rain from the higher regions of the atmosphere, but in greater measure to the heat absorbed owing to the rapid evaporation.

The cold produced by evaporation is used in hot climates to cool water by means of *alcarrazas*. These are porous earthen vessels, through which water percolates, so that on the outside there is a continual evaporation, which is accelerated when the vessels are placed in a current of air. For the same reason wine is cooled by wrapping the bottles in wet cloths and placing them in a draught.

The high temperatures which the body can sustain in Turkish baths—exceeding even the temperature of boiling water—are only possible by the rapid evaporation which sets in.

269. **Water and mercury frozen in a vacuum.**—From the great quantity of heat which disappears whenever a liquid is converted into vapour, it will be seen that by accelerating the evaporation we have a means of producing cold. We have found that liquids vaporise more rapidly the lower the pressure (263). Hence, if a vessel containing water be placed in a space from which the air is exhausted, it should cool very rapidly.

Leslie succeeded in freezing water by means of its own rapid evaporation. Under the receiver of the air-pump is placed a vessel containing strong sulphuric acid, a substance which has a great affinity for water, and above it a thin, shallow, porous capsule, A (fig. 280), containing a small quantity of water. By exhausting the receiver the water begins to boil, and, since the vapours are absorbed by the sulphuric acid as fast as they are formed, a rapid evaporation is produced, which quickly effects the freezing of the water.

Fig. 280.

By using liquids more volatile than water, more particularly liquid sulphurous acid, which boils at $-10°$, a degree of cold is obtained sufficiently intense to freeze mercury. The experiment may be made by covering the bulb of a thermometer with cotton-wool, and, after having moistened it with liquid sulphurous acid, placing it under the receiver of the air-pump. When the pressure is reduced the mercury is quickly frozen.

By passing a current of air, previously cooled, through liquid methyl chloride, temperatures of from $-23°$ to $-70°$ C. may be maintained with great constancy for several hours.

Thilorier, by directing a jet of liquid carbonic acid on the bulb of an alcohol thermometer, obtained a temperature of $-100°$ without freezing the alcohol. With a mixture of solid carbonic acid, liquid protoxide of nitrogen, and ether, Despretz obtained a sufficient degree of cold to reduce alcohol to the viscous state.

By means of the evaporation of bisulphide of carbon the formation of ice may be illustrated (fig. 281) without the aid of an air-pump. A little water is dropped on a small piece of wood, B, and a capsule of thin copper foil, C, containing bisulphide of carbon, is placed on the water. The evaporation of the bisulphide is accelerated by means of a pair of bellows, N, and after a few minutes the water freezes round the capsule, so that the latter adheres to the wood.

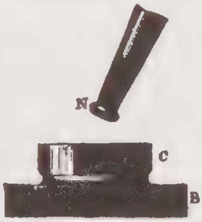


Fig. 281.

In like manner, if some water be placed in a test-tube, which is then dipped in a glass containing some ether, and a current of air be blown through the ether by means of a glass tube fitted to the nozzle of a pair of bellows, the rapid evaporation of the ether very soon freezes the water in the tube.

In Harrison's method of making ice artificially, a steam-engine is used to work an air-pump which produces a rapid evaporation of some ether, in which is immersed the vessel containing the water to be frozen. The apparatus is so constructed that the vaporised ether can be condensed and used again.

In the East Indies ice is formed even at a temperature of 8° to 10° C. provided the nights are clear and bright. Water is exposed in flat porous vessels, which are placed in shallow pits lined with bad conductors, such as straw. The water percolates through the porous vessel, and, there evaporating, withdraws so much heat from the vessel and from the rest of the water, that it freezes.

This process is favoured by the absence of aqueous vapour from the atmosphere ; for aqueous vapour has a great absorptive power for the obscure heat radiated from the earth (233) and thus obstructs it in its attempt to escape.

CHAPTER VIII

LIQUEFACTION OF VAPOURS AND GASES

270. **Liquefaction of vapours.**—The *liquefaction* or *condensation* of vapours is their passage from the aëriform to the liquid state. Condensation may be due to three causes—*cooling*, *compression*, or *chemical affinity*.

When vapours are condensed, their latent heat becomes free—that is, it affects the thermometer. This is readily seen when a current of steam at 100° is passed into a vessel of water at the ordinary temperature. The liquid becomes rapidly heated, and soon reaches 100°. The quantity of heat given up in liquefaction is equal to the quantity absorbed in vaporisation.

Liquefaction by chemical affinity. The affinity of certain substances for water is so great as to condense the vapours in the atmosphere, even when they are far from their point of saturation. Thus, when highly hygroscopic substances, such as quicklime, caustic potash, or sulphuric acid, are exposed in the air, they always absorb aqueous vapour. Certain varieties of common salt, exposed to the air, absorb and condense so much aqueous vapour as to become liquid. Many other salts, such as calcium chloride and sodium nitrate, have the same property, and are hence called *deliquescent salts*.

Liquefaction by pressure. Let us suppose a vessel containing aqueous vapour—a cylinder, for instance—and in this cylinder a piston which can be depressed at will, like that represented in fig. 3. When the piston is depressed, the vapour behaves like a true gas, as it is not at first in a state of saturation, the pressure increasing its elastic force and density without liquefying it. But the more the piston is depressed, the smaller does the volume of the vapour become, and a point is ultimately reached at which the vapour present is just sufficient to saturate the space. From this point the slightest increase of pressure causes a portion of vapour

to pass into the liquid state, and if the piston descends to the bottom of the cylinder all the vapour is condensed. In this experiment it is to be observed that when once saturation is attained, provided there is no air in the cylinder, the resistance to the depression of the piston does not increase in proportion as it descends, because, the vapour being saturated, its pressure does not increase with diminished volume.

Liquefaction by cooling. Cooling, as well as pressure, only causes vapours to liquefy when they are in a state of saturation. But when once a given space is saturated, the slightest lowering of temperature takes from the vapours the heat which gives them their condition, the attraction between the molecules preponderates, they agglomerate, forming extremely small droplets, which float in the air and are deposited on the surrounding bodies.

Vapours are ordinarily condensed by cooling. Thus the vapours exhaled from the noses and mouths of animals first saturate the colder air in which they are disengaged, and they then condense with a cloud-like appearance. Owing to the same phenomenon the vapours become visible which are disengaged from boiling water, those which rise from chimneys, the fogs formed above rivers, and so forth. All these vapours appear more distinctly in winter than in summer, for then the air is colder, and the condensation is more complete.

In cold weather, the windows in heated rooms are seen to become covered with dew on the inside. The air of these rooms is in general far from being saturated with vapour, but the layers of air in immediate contact with the windows become colder ; and as the quantity of vapour necessary to saturate a given space is less the colder the space, a moment is reached at which the air in contact with the windows is saturated, and then the vapour it contains is deposited. In a time of thaw, when the air is hotter on the outside than on the inside, the deposit is formed on the outside. To the same cause is due the deposit of moisture formed on walls, which is expressed by saying that they *sweat*—an unsuitable expression, for the moisture does not come from the walls, but from the atmosphere. The walls are colder than the air, and they lower the temperature of the layers in contact with them, and condense the aqueous vapour. A similar effect is produced when in summer a bottle of wine is brought from the cellar, or when a glass is filled with cold water : a deposit of dew is formed on the surface of these vessels. The same phenomenon does not occur so often

in winter, for then the temperature of the atmosphere being frequently the same as that of the bottle, or even lower, the layers of air in immediate contact with it are not cooled.

271. **Heat disengaged during condensation.**—It has been seen that any liquid in vaporising absorbs a quantity of heat. This heat is not destroyed, for in the converse change it reappears in the *sensible* state—that is to say, it is capable of acting on our sense of feeling and on the thermometer. For instance, we know that a pound of water absorbs in vaporising 540 units of heat (267)—that is to say, a quantity of heat necessary to raise 540 pounds of

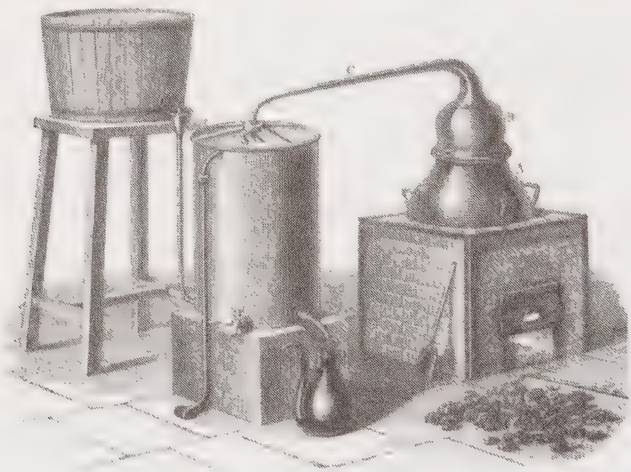


Fig. 282.

water from 0° to 1° : conversely, a pound of steam at 100°, which is liquefied and gives a pound of water at 100°, causes 540 units to pass from the latent to the sensible state—an amount of heat which is utilised in heating by steam. This amount is equal to that which would be capable of raising 4 pounds of cast iron to its melting-point.

The quantity of heat which becomes free when aqueous vapour is condensed is sometimes utilised for heating private houses, hot-houses, and public buildings. Steam is produced in boilers like those used in steam-engines, and passes thence into metal tubes

concealed behind the wainscot, or into columns which serve at the same time as ornaments for rooms. The steam condensing in these pipes gives up a considerable quantity of heat, which they impart to the surrounding air. The pipes being somewhat inclined, the condensed water flows back into the boiler, and thus a constant circulation is kept up.

272. **Distillation. Stills.**—*Distillation* is an operation by which volatile liquid may be separated from substances which it holds in solution, or by which liquids of different volatilities may be separated. The operation depends on conversion of liquid into vapour by the action of heat, and the condensation of the vapour by cooling.

The apparatus used in distillation is called a *still*. Its form may vary greatly, but it consists essentially of three parts : (1) the *body*, A (fig. 282), a copper vessel containing the liquid, the lowest part of which fits in the furnace ; (2) the *head*, B, which fits on the body, and from which a lateral tube, C, leads to (3) the *worm*, S, a long spiral tin or copper tube, placed in a cistern kept constantly full of cold water. The object of the worm is to condense the vapour, by exposing a great extent of surface to the cold water.

To free ordinary water from the many impurities which it often contains, it is placed in a still and heated. The vapour disengaged is condensed in the worm, and the distilled water arising from the condensation is collected in the receiver, D. The vapour, in condensing, rapidly heats the water in the cistern, which must, therefore, be constantly renewed. For this purpose a continual supply of cold water passes into the bottom of the cistern, while the heated, and therefore lighter, water rises to the surface, and issues by a tube in the top of the cistern.

Brandy is obtained from wine by means of distillation. Wine consists essentially of water, alcohol, and colouring matter ; when heated in a still to a temperature between 78° and 100°, the alcohol, which boils at 78°, vaporises, while water, which only boils at 100°, remains behind, or at all events only passes over in small quantity. The liquid which passes over in this distillation is brandy, which is in effect dilute alcohol.

273. **Apparatus for determining the alcoholic value of wines.**—One of the forms of this apparatus consists of a glass flask resting on a tripod, and heated by a spirit-lamp (fig. 283). By means of an india rubber tube this is connected with a worm placed in a copper vessel filled with cold water, below which is a test-glass for

collecting the distillate. On this are three divisions—one, *a*, which measures the quantity of wine taken : the two others indicating one half and one third of this volume.

The measure is filled up to *a* with wine, which is then poured into the flask, and, this having been connected with the worm, the distillation is commenced. The liquid which distils over is a mixture of alcohol and water. For ordinary wines, such as claret and hocks, about one third is distilled over ; and for wines richer in spirit, such as sherries and ports, one half must be distilled : experiment has shown that in these circumstances all the alcohol passes over in the distillate. The measure is then filled up with distilled water

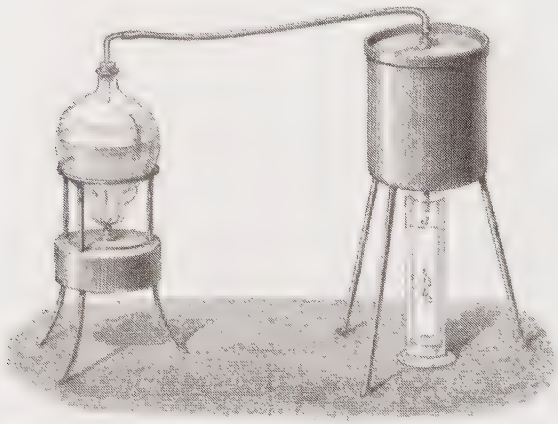


Fig. 283.

to *a* ; this gives the mixture of alcohol and water of the same volume as the wine taken, free from all solid matters, such as sugar, colouring matter, and acid, but containing all the alcohol. The specific gravity of this distillate is then taken by means of an alcoholometer (116), and the number thus obtained corresponds to a certain strength of alcohol as indicated by the tables.

274. **Liquefaction of gases.**—We have already seen (270) that a saturated vapour, the temperature of which is constant, is liquefied by diminishing the volume, and that, the volume remaining constant, it is brought into the liquid state by lowering the temperature.

Unsaturated vapours behave in all respects like gases. And it is natural to suppose that what are ordinarily called *permanent gases* are really unsaturated vapours. For the gaseous form is accidental and is not inherent in the nature of the substance. At ordinary temperatures sulphurous acid is a gas, while in countries near the Poles it is a liquid ; in temperate climates ether is a liquid—at a tropical temperature it is a gas. And just as unsaturated vapours may be brought to the state of saturation, and be then liquefied by suitably diminishing the temperature or increasing the pressure, so, by the same means, gases may be liquefied. But, as they are mostly very far removed from this state of saturation, great cold and pressure are required. Some of them may, indeed, be liquefied either by cold or by pressure ; for the majority, however, both processes must be simultaneously employed. No gases can resist these combined actions, and those which for long resisted all attempts to liquefy them—hydrogen, oxygen, nitrogen, nitric oxide, and carbonic oxide—become liquid when submitted to a sufficient degree of cold and pressure.

For every gas there is a temperature above which it cannot be liquefied, however great be the pressure applied ; this is called the *critical temperature* of the gas ; in the case of carbonic acid it is 31°. The pressure which must be applied to a gas at the critical temperature in order to liquefy it is called the *critical pressure* ; for carbonic acid it is 73 atmospheres. The lower is the temperature of a gas below the critical temperature the less is the pressure required to liquefy it ; thus carbonic acid at 13° requires 45 atmospheres and only 35 at 0°.

Fig. 284.

In the case of oxygen the critical temperature is $-119°$ C., and the critical pressure 470 atmospheres.

Fig. 284 illustrates the principle of the method by which Faraday liquefied certain gases ; in one limb of a stout bent glass tube are placed the substances which act chemically on each other and evolve the gas to be liquefied ; the other limb is hermetically sealed. On heating the right limb in an oil bath the gas is disengaged, and in the degree in which this occurs the pressure

increases, and the gas ultimately liquefies and collects in the other leg ; the process is accelerated by placing this in a freezing mixture.

One of the most remarkable of the early experiments on the liquefaction of gases is that made by Thilorier to liquefy and solidify carbonic acid. The principle of the method is that of Faraday. The apparatus used by Thilorier consists of two cast-iron cylinders with very thick sides, of 5 to 6 quarts capacity (fig. 285). They are hermetically closed, and are connected by means of a leaden tube.

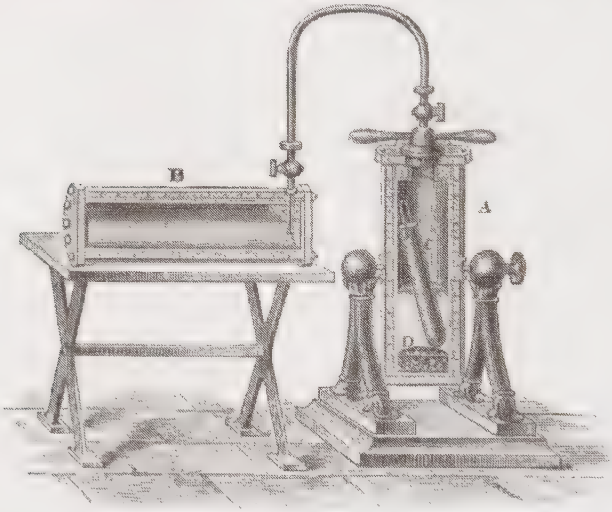


Fig. 285.

In one of these cylinders, A, called the *generator*, are placed the substances by whose chemical action carbonic acid is evolved. These are ordinarily sodium bicarbonate, D, and sulphuric acid in the tube, C. The second cylinder, called the *receiver*, B, is empty ; and the gas disengaged by the chemical action in the generator distils over, and, as the receiver is colder, it condenses in virtue of its increasing pressure. As much as two quarts of liquid carbonic acid have thus been prepared.

At a temperature of 15° the pressure of the gas in the cylinders is not less than 50 atmospheres ; a pressure which would burst the

vessels if they were not of great strength. An accident of this kind happened some years ago, and caused the death of Thilorier's assistant.

To obtain solid carbonic acid, the receiver is provided with a stopcock attached to a tube, which dips in the liquefied gas. On opening this stopcock, the liquid, driven by pressure, jets out; passing then from a pressure of 50 atmospheres down to a single one, a part of the liquid volatilises; and, in consequence of the heat absorbed by this evaporation, the rest is so much cooled as to solidify in white flakes like snow or anhydrous phosphoric acid.

Solid carbonic acid evaporates very slowly, and is a perfectly harmless substance. By means of an alcohol thermometer its temperature has been found to be about $-90°$. A small quantity placed on the hand does not produce the sensation of such great

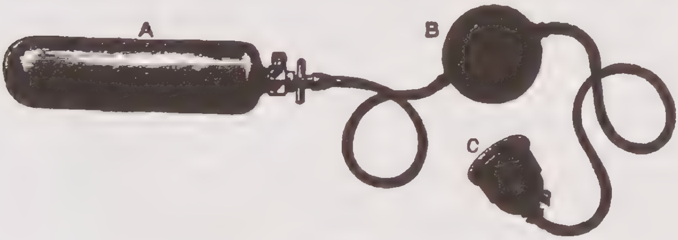


Fig. 286.

cold as might be expected. This arises from the imperfect contact. But if the solid be mixed with ether, the cold produced is so intense that when a little is placed on the skin all the effects of a severe burn are produced. Such a mixture of the two substances solidifies four times its weight of mercury in a few minutes. When a tube containing liquid carbonic acid is placed in this mixture the liquid becomes solid, and looks like a transparent piece of ice. When this mixture is placed under the receiver of an air-pump and rarefaction produced the temperature sinks to $-110°$. Liquid nitrous oxide solidifies in consequence of the cold produced by its volatilisation forming a mass the melting-point of which is $-105°$ C.

The condensation of gases is now carried out on an industrial scale. The gases contained in gasholders are condensed in cylinders of about a cubic foot capacity, A (fig. 286), by an arrange-

ment similar in principle to that of the air-gun (fig. 156). When used for inhalation of nitrous oxide or oxygen an india-rubber bag, B, is attached which, when the gas is allowed to issue by turning the screw 'cock, C, becomes inflated, and, by means of a suitable india-rubber mouth-piece, can be used for inhalation. Nitrous oxide is thus applied for anæsthetic purposes.

For convenience in general use various forms of reducing valves and regulators have been constructed, by which the high pressure of the issuing stream of gas is reduced to any amount—as low as a few inches of water if desired. This is then automatically maintained constant till the cylinder is empty. The gases are often used direct from the cylinders, the regulation being effected by means of the cylinder valve itself.

Oxygen and hydrogen are also extensively used in this way for the oxyhydrogen light. The gases are supplied under a pressure of 120 atmospheres, and before being used the cylinders are tested by hydraulic pressure up to 185 atmospheres, or over one ton on the square inch.

In 1877, Pictet and Cailletet independently succeeded in producing small quantities of liquid oxygen. As already stated, no amount of pressure will liquefy a gas unless its temperature has previously been reduced below its critical value, and this critical temperature for oxygen is $-119°$ C. We can thus understand why the early experimenters did not succeed in liquefying oxygen, nitrogen, etc.

The general nature of the process by which the low temperatures necessary for the liquefaction of these gases are attained is as follows: Liquid sulphurous acid boils at $-10°$ under atmospheric pressure (262). By means of two double-acting pumps sulphurous acid may be rapidly evaporated, and the vapour again condensed into liquid under pressure and cooled by ice. The cooled liquid is again vaporised under low pressure, and so on, the process being a continuous circulatory one. In this way the sulphurous acid is reduced to a temperature of $-65°$. Its function is to produce a large quantity of liquid carbonic acid, which is then subjected to a perfectly analogous process of rarefaction and condensation, and is used to liquefy ethylene, which boils—at atmospheric pressure—at $-103°$. This substance, by evaporation at low pressure, enables a temperature to be reached sufficiently low to liquefy oxygen ($-182°$ at atmospheric pressure, but $-136°$ at a pressure of 20 atmospheres). Nitrogen liquefies at $-194°$, and atmospheric air at $-192°$.

Hydrogen is much more difficult to liquefy on account of its low critical temperature ($-235°$ C.), but its liquefaction has been effected by Dewar and others. The boiling point of hydrogen is -253, and its solidifying point 5 degrees lower. It is usual to measure these low temperatures from $-273°$, the absolute zero of temperature ; thus hydrogen is said to boil at 20° (abs.) and to melt at 15° (abs.).

CHAPTER IX

SPECIFIC HEAT. CALORIMETRY

275. **Calorimetry. Thermal unit.**—The province of calorimetry is the measurement of the *quantity of heat* which a body parts with or absorbs when its temperature sinks or rises through a certain number of degrees, or when it changes its condition.

We must distinguish between *quantity of heat* and *temperature* (214); the temperature of a red-hot iron poker will be considerably higher than that of a bucket of hot water, but the quantity of heat in the latter case will be greater. A quantity of heat may be expressed by any of its effects which can be directly measured, but the most convenient is the alteration of temperature; and quantities of heat are usually defined by stating the extent to which they are capable of raising the temperature of a known weight of a substance, such as water.

The unit chosen for comparison, and called the *thermal unit*, is not everywhere the same. In France it is the quantity of heat necessary to raise the temperature of *one* kilogramme of water through *one* degree Centigrade; this is called the *calorie*. In this book we shall adopt, as a thermal unit, *the quantity of heat necessary to raise one pound of water through one degree Centigrade*; 1 *calorie* = 2·2 thermal units, and one thermal unit = 0·45 *calorie*.

276. **Specific heat.**—When equal weights of two different substances at the same temperature—mercury and water, for example—are placed in similar vessels and subjected for the same length of time to the heat of the same lamp, or are placed at the same distance in front of the same fire, it is found that after a time their temperatures will differ considerably; the mercury will be much hotter than the water. But as, from the conditions of the experiment, they have, during all this time, been receiving heat at the same rate, it is clear that the quantity of heat which is sufficient to raise the temperature of mercury through a certain number

of degrees will only raise the temperature of the same quantity of water through a less number of degrees—in other words, that it requires more heat to raise the temperature of water through one degree than it does to raise the temperature of an equal quantity of mercury by the same amount. Conversely, if the same quantities of water and of mercury at 100° C. be allowed to cool down to the temperature of the atmosphere, the water will require a much longer time for this purpose than the mercury; hence, in cooling through the same number of degrees, water gives out more heat than does mercury.

The difference of the specific heats of solids may be illustrated by means of the apparatus depicted in fig. 287, which represents two equal vessels, *c* and *c'*, containing equal weights of water at the same temperature. These vessels are each embedded in an outer vessel, *d* and *d'*, a non-conducting layer of cotton wool being placed between. Two coils, one of sheet iron, *a'*, and the other of sheet lead, *a*, of the same weight, are heated in an air-bath to the same high temperature, and are then rapidly introduced into the water through the apertures in the lids, *b* and *b'*, so as to rest on the perforated discs, *s* and *s'*. These can be moved up and down so as to equalise the temperature throughout the liquid. When the respective thermometers, *t* and *t'*, cease to rise, they are read off, and it is seen that the temperature indicated by the thermometer in which is the iron is decidedly higher than that in which is the lead.

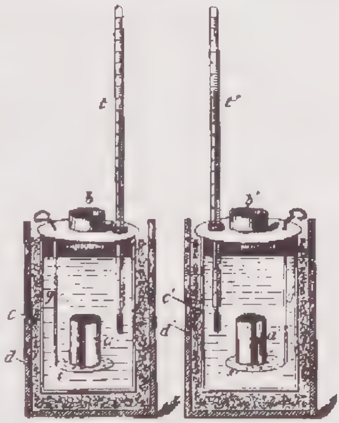


Fig. 287.

If a pound of water at 100° is mixed with a pound of water at zero, the mixture has a temperature of 50°. But if a pound of mercury at 100° is mixed with a pound of water at zero, the temperature of the mixture will only be about 3°—that is to say, while the mercury has cooled through 97°, the temperature of the water has only been raised 3°. Consequently, for the same weight, water

requires about 32 times as much heat as mercury does to exhibit the same rise of temperature.

Again, if a pound of water at 10° be shaken with a pound of turpentine at 60°, the temperature of the mixture will be about 24°. So that the heat which turpentine gives out in sinking through 36 degrees will only raise the temperature of an equal weight of water through 14 degrees; or, in other words, the heat required to raise turpentine through a certain range of temperature is only about two-fifths of that required to raise the same weight of water through the same range.

If similar experiments are made with other substances, it will be found that the quantity of heat required to effect a certain change of temperature is different for almost every substance; and we speak of the *specific heat* of a body as the quantity of heat which it absorbs when its temperature rises through a given range of temperature—from 0° to 1°, for example—compared with the quantity of heat which would be absorbed under the same circumstances by the same weight of water. In other words, water is taken as the standard for the comparison of specific heats. Thus, to say that the specific heat of silver is 0·057 means that the quantity of heat which would raise the temperature of any given weight of silver through 1° C. would only raise the temperature of the same weight of water through 0·057° C., or that the quantity of heat which would raise a given weight of water through 1° C. would raise the same weight of silver through 17·5° C.

The specific heat of water being unity, that of air is 0·237 if we compare *equal weights* of the two substances. Hence a pound of water in losing one degree of temperature would raise the temperature of 4·2 pounds of air through one degree. But as water is 770 times as heavy as air, if we compare *equal volumes*, a cubic foot of water in sinking through one degree of temperature would raise 3,234 cubic feet of air one degree.

277. **Determination of the specific heats of solids and of liquids.**—Three methods have been employed for determining the specific heats of bodies: (i.) the method of melting ice, (ii.) the method of mixtures, and (iii.) that of cooling.

Method of the fusion of ice. This method of determining specific heats is based on the fact that to melt a pound of ice 80 thermal units are necessary. The substance whose specific heat is to be determined is raised to a known temperature—100°, for instance—and is then rapidly placed in ice. In cooling from 100° to zero,

the body melts a certain quantity of ice, which is collected in the form of water. From the weight of this water, from that of the body, and from the number of degrees through which it is cooled, the specific heat may be readily deduced by a simple calculation.

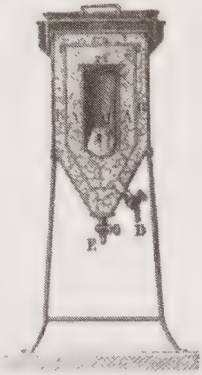


Fig. 288.

Lavoisier and Laplace's *ice calorimeter* is represented in section in fig. 288. It consists of three concentric tin vessels, M, A, B, each with a cover of the same material; in the central one is placed the body, M, whose specific heat is to be determined, while the spaces between M and A, and between A and B, are filled with pounded ice. The ice in the compartment A is melted by the heated body, and the water resulting from the liquefaction runs off by the stopcock D, and is collected in a vessel; the ice in the compartment B cuts off the heating influence of the surrounding atmosphere. The stopcock E gives issue to the water which arises from the liquefaction of the ice in B.

Method of mixtures. This is a much more accurate and convenient method than that of the fusion of ice, and is essentially that of the experiments cited above to establish the fact of specific heat. The solid body whose specific heat is to be determined is weighed and raised to a known temperature, by being kept, for instance, for some time in a closed space heated by steam; it is then immersed in a mass of cold water, the weight and temperature of which are known. The water becomes warmed by the heat given up by the body in cooling, and both come at last to the same temperature. From this common temperature, from the respective weights of the water and of the

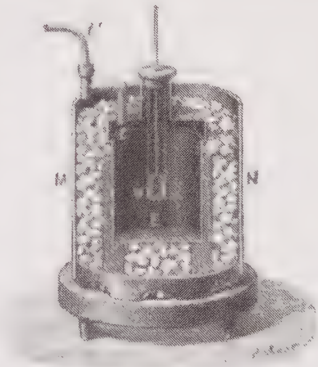


Fig. 289.

substance, and, lastly, from their temperatures at the time of mixture, the specific heat of the body is deduced by a simple calculation.

278. **Method of cooling.**—Equal weights of different bodies whose specific heats are different, occupy different times in cooling through the same number of degrees. This principle is applied in determining the specific heats of liquids in the following manner:—A small polished silver vessel, V (fig. 289), is filled with the liquid, and a thermometer placed in it. This vessel is heated to a certain temperature, and is then introduced into a copper vessel, E, in which it fits hermetically. This copper vessel is exhausted through the tube tt', and maintained at the constant temperature of melting ice, MN, and the time noted which the substance takes in falling through a given range of temperature, from 15° to 5° for example. The experiment is repeated with a standard liquid, and the times which equal weights of different bodies require for cooling through the same range of temperature are directly as their specific heats.

Substances	Specific heats	Substances	Specific heats
Water	1·0000	Zinc	0·0955
Turpentine	0·4256	Copper	0·0951
Wood charcoal	0·2411	Silver	0·0570
Sulphur	0·2025	Tin	0·0552
Graphite	0·2018	Antimony	0·0507
Thermometer glass	0·1976	Mercury	0·0333
Phosphorus	0·1895	Gold	0·0324
Diamond	0·1469	Platinum	0·0324
Iron	0·1138	Lead	0·0314
Nickel	0·1086	Bismuth	0·0308

It will be seen from the above table that water and oil of turpentine have a much greater specific heat than that of other substances, and more especially than the metals. It is from its great specific heat that water requires a relatively long time in being heated or cooled; and that, for the same weight and temperature, it absorbs or gives out far more heat than other substances. This double property is applied in heating by hot water, and it plays a most important part in the economy of nature.

Those bodies which have great specific heat, and therefore which require a great quantity of heat to raise them to a given

temperature, also give out a great quantity in cooling through the same range. This difference between bodies as to the quantities of heat they contain may be illustrated by a simple experiment. A number of equal bullets of various metals, iron, lead, bismuth, and copper, are heated to a temperature of about 200° C. by

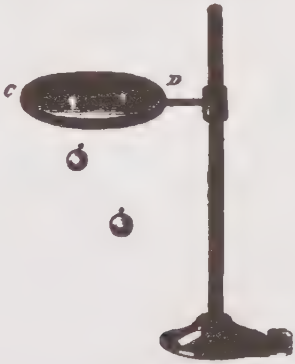


Fig. 290.

immersing them in hot oil; they are then placed on a cake of beeswax, CD, about half an inch in thickness (fig. 290). It will then be found that the iron and copper melt through, while the lead and bismuth make but little way, being unable to sink much more than half their way through the wax.

CHAPTER X

STEAM-ENGINE

279. **Invention of the steam-engine.**—The *steam-engine* is undoubtedly the most important of the applications of the physical sciences. Based on the very great elastic force which aqueous vapour assumes at a high temperature (256) and on the condensation of this vapour by cooling (270), the steam-engine, in a small volume and at a small expense, produces very considerable motive power.

It is by the successive efforts of several men of genius that the steam-engine has attained its present simplicity and precision.

Its history begins with Hero, the inventor of the fountain which bears his name, who invented, nearly two thousand years ago, a steam tourniquet known as the *eolipyle*, analogous to the hydraulic tourniquet (fig. 84). The names of Salomon of Caux, and of the Marquis of Worcester, are mentioned in the history of the steam-engine.

Denis Papin, a French physicist, to whom is due the apparatus already described (264), was the first who caused a piston to ascend in a vertical cylinder, closed at the bottom and open at the top, by means of the elastic force of steam, and to descend by condensing this vapour by cooling; so that the piston which descended in virtue of atmospheric pressure had an up-and-down motion in the cylinder, which is still the principle of all steam-engines. Papin, who was a Protestant, was obliged to fly from France, in consequence of the revocation of the Edict of Nantes, and the description and plan of his machine were published in Germany in 1690. He even made a model large enough to move a boat by means of paddle-wheels. In this model there was water underneath the piston at the bottom of the cylinder. When a furnace was placed under this, the water was converted into steam, and its elastic force

raised the piston ; when the piston was at the top of its course the furnace was withdrawn : the cylinder cooling, the steam was condensed, and the piston sank.

In 1705 Newcomen and Cawley constructed a steam-engine, or 'fire-pump,' as it was then called, the object of which was to drain mines. In this engine (fig. 291) the steam was produced separately in a boiler, *m*, below the cylinder, *c*, containing the piston, *p*. The condensation also was effected by cold water from a cistern, *n*, being injected into the cylinder through a cock, *b*. This was opened when the piston was to descend, the descent being effected by atmospheric pressure, and was closed after the descent ; a second one, *a*, was opened, through which steam entered, and so on. But the sides of the cylinder being cooled by this injection of cold water, the steam which filled it was partially condensed, until the sides were again heated ; there was thus a considerable loss of steam, and therefore of fuel. The condensed water flowed out by a pipe, at the end of which was the valve, *v*, which opened as the piston, *p*, descended. *ww* is the beam by which the motion is transmitted to the pump-rod *d*.

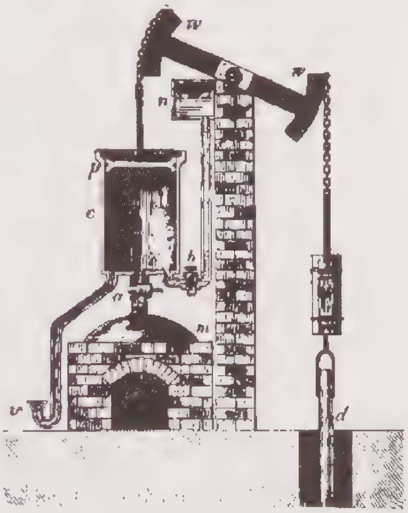


Fig. 291.

280. **Watt's improvements in the steam-engine.**—James Watt, a mathematical-instrument maker in Glasgow, had to repair the model of a Newcomen's engine belonging to the physical cabinet of the University. Struck by the enormous quantity of steam and of condensing water used by this engine, he entered upon a long series of researches and improvements, which he pursued with admirable perseverance for fifty years, without ever being content with the success he obtained. Thus it was that Newcomen's

machine, successively changed and improved in all its parts, at last really became Watt's machine.

Condenser. Watt's first and principal invention was that of the *condenser.*

This name is given to a closed vessel quite distinct from the cylinder in which the piston moves, and only connected with it by a tube provided with a stopcock. In this vessel cold water is injected, and the vapour is condensed by opening the connecting stopcock. Thus, as the side of the cylinder is not cooled, all the steam which enters there is utilised. Thus there was effected so great an economy of steam, and therefore of fuel, that Watt and Boulton (his partner), having taken a patent, realised great profits by only requiring, for a certain number of years, a third of the saving in the consumption of coal, as compared with Newcomen's engine.

Single-acting engine. In Newcomen's engine, the cylinder of which was open at the top, the steam only lifted the piston ; and then, when the steam was condensed, the pressure of the atmosphere brought it down again ; whence the name *atmospheric engine*, by which it was designated. As the piston descended, air passed into the cylinder and cooled the sides, in consequence of which a portion of the vapour which entered the cylinder was condensed until the sides were again heated. To remove this source of loss, Watt closed the cylinder altogether, and caused the vapour to act above the piston, so as to make it descend ; then, by an arrangement of stopcocks, alternately opened and closed by the action of the engine itself, the steam passed simultaneously above and below the piston. This, being pressed equally in opposite directions, remained in equilibrium ; so that a simple counterpoise, acting by means of a lever at the end of a piston-rod, raised the piston again, and so on. This machine, into which the air did not enter, and where the atmospheric pressure did not act, was called the *single-acting engine*, to express that the steam had a useful action on only one side of the piston.

The single-acting engine had the great disadvantage that it had no real force except when the piston was descending. It could transmit motion to pumps for emptying mines, because, for that, effort in only one direction was required ; but it would not furnish a sufficiently regular motion for many industries—for cotton manufactures, for instance. Hence Watt's task was not completed, but he was not long in finding another plan.

Double-acting engine. In this engine, one form of which we

shall presently describe, and which is represented in fig. 292, the cylinder is closed both at the top and at the bottom, but the steam acts alternately on the two faces of the piston—that is to say, by a system of valves, opened and closed by the engine itself, when the lower part of the cylinder communicates with the condenser, the upper part is connected with the boiler, and the steam, acting on the piston, causes it to descend. Then, when the piston is at the bottom of its stroke, the parts change: the top of the cylinder is in connection with the condenser, and the bottom with the boiler; the piston rises again, and so forth, whence results an alternating rectilinear motion, which is changed into a continuous circular motion, as will be presently described (281).

Air-pump. Watt completed his engine by the addition of three pumps, which are worked by the engine, and play an important part. For the cold water of the condenser becomes rapidly heated by the heat which the steam gives up to it (271), and this water, soon reaching 100°, would no longer condense the steam. Moreover, the air, which is always dissolved in cold water, is liberated in the boiler, owing to the increase in temperature. Now, this air, passing both above and below the piston, would soon stop its motion. To prevent these two injurious effects, Watt applied to the engine a suction-pump, which continually withdrew from the condenser the air and water which tended to accumulate there.

Feed-pump and cold-water pump. The two other pumps which Watt added are the feed-pump and the cold-water pump. The first is a force-pump which sends into the boilers the hot water withdrawn from the condenser by the air-pump, thus producing a considerable saving in fuel. The other is a suction-pump, which raises, either from a well or a river, or some other source, the cold water intended to replace that heated in the condenser and withdrawn by the air-pump.

Besides the important parts which have thus been described, we owe to Watt the arrangement for distributing the steam alternately above and below the piston; the *regulator*, whose function, when the machine works too slowly, is to admit more steam into the cylinder, and, on the other hand, to diminish the quantity when the velocity is too great; lastly, the *parallelogram*, devised by Watt, which imparts to the piston-rod a rectilinear motion. It may be added that Watt, who began life as a philosophical-instrument maker, carried into the execution of these great pieces of machinery the same perfection as is required for the best scientific instrument.

281. **Description of the double-acting engine.**—We have already seen that the double-acting engine is that in which the

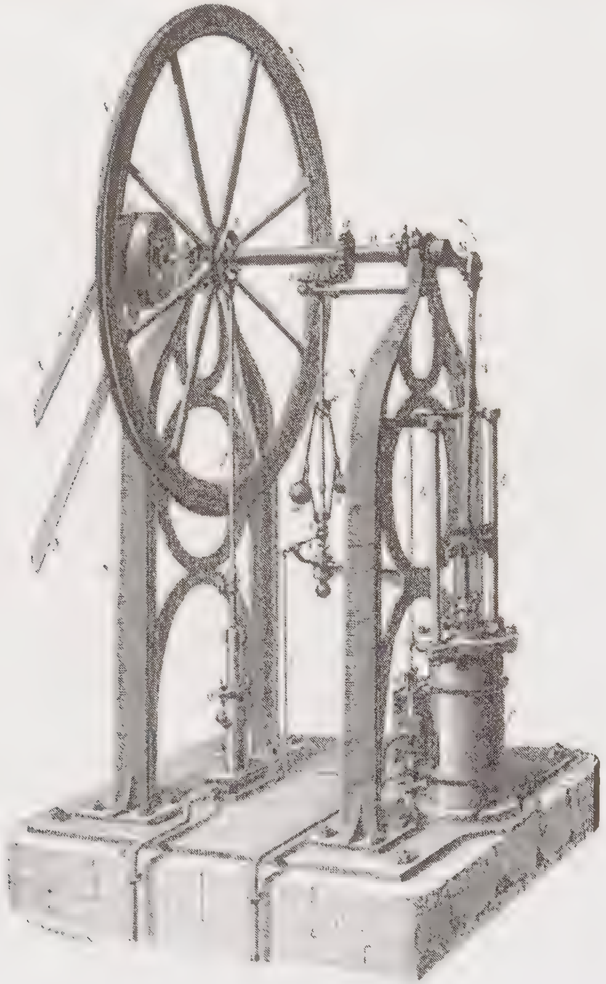


Fig. 292.

steam acts alternately above and below the piston (280). Fig. 292 represents an engine of this kind, and fig. 296 gives a section of the cylinder, of the piston, and of the distribution of steam. The entire engine is of iron. To the piston, T, is fixed a rod, A, which slides with gentle friction in a tubulure, U, placed at the centre of the plate which closes the cylinder (fig. 296). As it is very important that no steam shall escape between the piston-rod and this tubulure, the latter is formed of two pieces, one attached to the plate, while the other, which fits in the first, can be pressed as tightly as is desired, so as to compress the material soaked with fat which is between the two tubulures. This arrangement is called a *stuffing-box*; it prevents the escape of steam without interfering with the motion of the piston-rod.

On the two sides of the cylinder are two columns, *h*, *h* (fig. 292), which guide the piston-rod in its upward and downward motion. The end of the piston-rod is connected with a long piece, B, called the *connecting-rod*, which in turn is jointed with a shorter piece, M, called the *crank*, the length of which is just half that of the stroke of the piston. The crank is rigidly fixed to a *horizontal shaft*, D, so that it cannot move without transmitting its motion.

By means of this connecting-rod and crank, the alternating rectilinear motion of the piston and of the rod is changed into a continuous circular motion; for the rod, during the ascent of the piston, acts upwards upon the crank, making it turn in the direction of the arrow. When the piston is at the top of its stroke the connecting-rod and the crank are vertical, one in front of the other. As the piston descends the connecting-rod again acts, so as always to turn the shaft in the same direction; and when the piston is at the bottom of the stroke, crank and connecting-rod are again vertical, but one is in the prolongation of the other. Hence it follows that the shaft, which has made half a turn during the ascent, makes a second one during the descent, and thus performs a complete revolution during each double oscillation of the piston.

To transmit the motion to machinery, on the shaft, D, is fixed a pulley, G, on which works an *endless band*, X Y, of leather, which works on another pulley fixed to the machinery to be turned. Moved by the first pulley, this band communicates its motion to the second; in this manner the motion is transmitted to all the workshops of a large factory. On the right of the fixed pulley, G, there is a second, which is not fixed to the horizontal shaft. This is the loose pulley. Its object is to suspend all the motion

in the machine without stopping the steam-engine. By means of an iron fork, not seen in the figure, which encloses the band, the latter may be slid from the fixed to the movable pulley. As this pulley is not connected with the horizontal shaft, the motion of the latter is not transmitted to it.

On the horizontal shaft is a very large iron wheel, V, called the *fly-wheel*, which is necessary for keeping up the motion ; for each time that the piston is at the top or bottom of its stroke there is a momentary arrest, during which the motion of the whole machine tends to stop. These are called the *dead points*. It is then that the fly-wheel, in virtue of its inertia and of its acquired velocity, moves the horizontal shaft, and thus keeps up a regular motion.

282. **Excentric. Slide-valve.**—The excentric is an arrangement by which a continuous circular motion is changed into an alternating rectilinear motion. It is very frequently used in machinery.

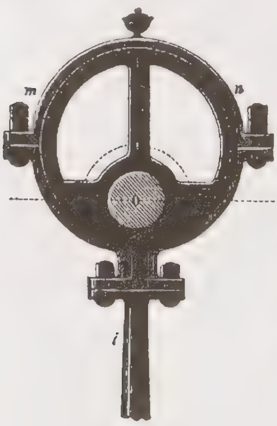


Fig. 293.

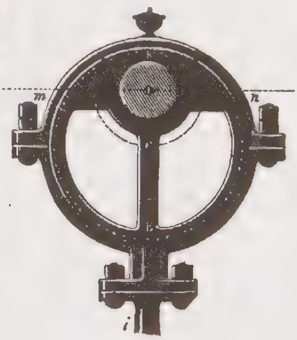


Fig. 294.

One of these is fitted to the horizontal shaft at E, and the other at *e* (fig. 292). The former works the *feed-pump*, and the latter the *slide-valve*. The action of each is the same. Figs. 293 and 294 represent it on a larger scale, in two exactly opposite positions. It consists of a circular piece, KE, fixed to the horizontal shaft, but

in such a manner that the centre of rotation does not coincide with the centre of the piece ; the latter being at C, the former at O. It follows from this construction that the point C constantly describes a circle about O, which is represented in the drawing by a dotted line. Hence, in each half-turn it passes from the position represented in fig. 293 to that represented in fig. 294, and *vice versâ*.

To use this motion, the excentric is surrounded by a *collar*, *m n*, in which it can turn freely like an axle in its box ; hence, during the rotation of the horizontal shaft, the collar shares the ascending and descending motion of the point C, but not its rotatory motion. The excentric alone turns, the collar only rises and sinks. By thus transmitting its motion to a rod, *i*, it works the slide valve, or the feed pump.

Slide-valve.—We have still to describe the slide-valve and valve-chest, the arrangement by which steam passes alternately above and below the piston. Figs. 295 and 296 present a vertical section of these parts and of the cylinder. The steam enters the valve-chest from the boiler by the brass tube *x*. From the valve-chest two conduits, *a* and *b*, are connected with the cylinder, one above and the other below. If they were both open at once, the steam, acting equally on the two faces of the piston, would keep it at rest. But one of these is always closed by the *slide-valve*, *y*, fixed to a rod, *i*. This moves alternately up and down, by means of the excentric, *e* (fig. 292), on the horizontal shaft as described above. In fig. 296 the slide-valve closes the conduit *a*, and, allowing the steam to enter at *b*, below the piston, the latter rises. But when it reaches the top of the stroke the excentric passes from the position represented in fig. 293 to that in fig. 294 ; hence the rod *i* sinks, and with it the slide-valve, which then closes the conduit, *b*, and allows the steam to enter at *a* (fig. 295). The piston then sinks, and so forth at each displacement of the slide-valve.

In completing this account of the manner in which steam is distributed, it remains to explain what happens when the steam presses below the piston (fig. 296). It must not remain above, otherwise the piston could not move. But while the steam enters below by the conduit *b*, the top of the cylinder, by means of the conduit *a*, is connected with a cavity, O, from which passes the tube L (fig. 292). Through this tube the steam which has already acted upon the piston passes into the atmosphere, or else is condensed in a vessel filled with cold water, which has been already mentioned—the

condenser (280). If, on the other hand, the piston sinks, the slide-valve being in the position of fig. 295, the vapour below the piston passes, by the conduit *b*, to the cavity O, and to the tube L.

283. **Regulator or governor.**—The object of this arrangement is to regulate or govern the quantity of steam which reaches the valve-chest, increasing it when the machine works too slowly and diminishing it when it works too rapidly. It consists of a parallelogram, *kr* (fig. 292), each angle of which is jointed. A toothed bevelled wheel, *a*, connected with the horizontal shaft, transmits its motion to a similar wheel, *b*, fixed to the rod, *c*, which supports the parallelogram. This turns, then, with the rod the more rapidly the greater the speed of the shaft. But the two upper arms are provided with solid balls, *m* and *n*; moreover, a socket, *r*, to which are attached the two lower arms, is not fixed to the rod *c*, but can glide along it. Hence the centrifugal force (31) acting on the balls *m* and *n* makes them diverge, the parallelogram opens and the socket rises. It transmits its motion to a lever, *s*, the short arm of which, being lowered, presses upon a long rod, *t*. This, inclining the lever O, effects a small rotation in a valve placed in the tube *x*, by which steam comes (figs. 295, 296). This valve, by opening or closing, admits more or less steam.

Fig. 295.

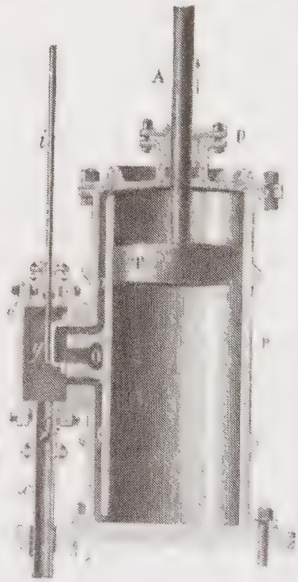


Fig. 296.

284. **Feed-pump.**—The object of this, as its name implies, is to replace the water in the boiler as fast as it evaporates. In fig. 292

this pump, placed at Q, on the left of the drawing, receives its motion from an excentric by means of a long rod, and it works both as *cold-water pump* and as *feed-pump*: as cold-water pump, inasmuch as it withdraws water from a well by a suction-pipe placed below the engine; and as feed-pump by its then forcing water into the boiler by the pipe R.

285. **Various kinds of steam-engines.**—A *low-pressure engine* is one in which the pressure of the steam is not much more than that of an atmosphere; and a *high-pressure engine* is one in which the pressure of the steam usually exceeds this amount considerably. Low-pressure engines are mostly *condensing engines*—in other words, they generally have a condenser where the steam becomes condensed after having acted on the piston: on the other hand, *high-pressure engines* are frequently without a condenser; the locomotive is an example.

If the communication between the cylinder and the boiler remains open during the whole motion of the piston, the steam retains practically the same pressure, and is said to act *without expansion*; but if, by a suitable arrangement of the slide-valve, the steam ceases to pass into the cylinder when the piston is at $\frac{1}{3}$ or $\frac{3}{4}$ of its course, then the steam *expands*—that is to say, in virtue of its elastic force, which is due to the high temperature, it still acts on the piston and causes it to finish its course. Hence a distinction is made between engines *expanding* and *non-expanding* with steam.

The principle of expansion is not applicable to low-pressure engines, for the elastic force of the steam is not great. But for high or mean pressure engines it not only effects a great saving in steam, and therefore in fuel, but it regulates the motion by diminishing the pressure the moment the acquired velocity of the piston tends to increase.

286. **Work of an engine. Horse-power.**—The work of an engine is measured by the mean pressure on the piston, multiplied by the area of the piston, and by the length of the stroke. In England the unit of work is the *foot-pound*—that is, the work performed in raising a weight of one pound through a height of a foot. Thus, to raise a weight of 14 pounds through a height of 20 feet would require 280 foot-pounds. In France the *kilogrammetre* is used—that is, the work performed in raising a kilogramme through a metre. This unit corresponds to 7·233 foot-pounds.

The *rate of work* in machines is the amount of work performed in a given time—a second or an hour, for example. In England the rates of work are compared by means of *horse-power*, which is a conventional unit, and represents 33,000 foot-pounds per minute or 550 per second. In France a similar unit is used, called the *cheval-vapeur*, which represents the work performed in raising 75 kilogrammes through one metre in a second. It is equal to about 542 foot-pounds per second.

Thus, suppose a steam-engine with a piston the area of which is 30 square inches, and its length of stroke 18 inches, and that it

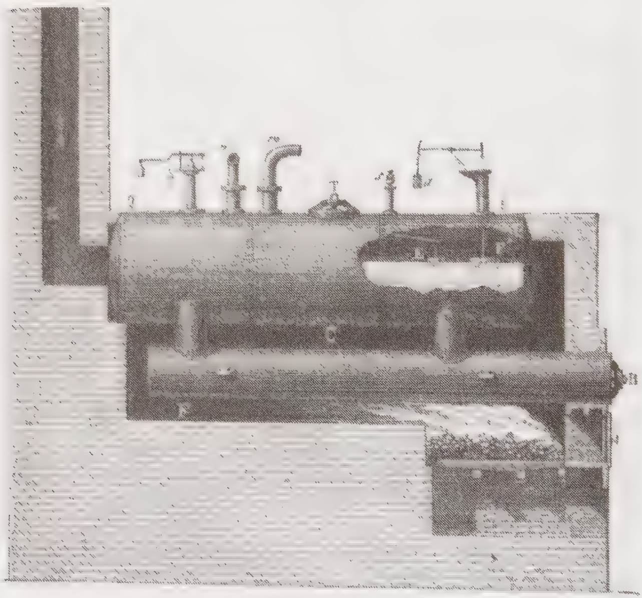


Fig. 297.

makes 84 up and down strokes in a minute. Suppose, further, that the mean pressure on the piston is equal to 14 pounds on a square inch. The work that the steam-engine performs is equal to $30 \times 14 \times 84 \times 2 \times 1\frac{1}{2} = 105{,}840$ foot-pounds per minute. From this must be deducted the work expended in overcoming the friction of the machine, working the pumps, etc. Taking these at 35 per

cent., there remains a useful effect of 68,796 foot-pounds per minute, which, from what has been said above, represents about 2 horse-power.

287. **Steam-boiler.**—We have still to describe the steam-boiler, or the arrangement by which the steam is generated, and its various accessories. Fig. 297 gives a longitudinal and fig. 298 a transverse section of a steam-boiler and its furnace. The steam-boiler consists of a long wrought-iron cylinder, PQ, with hemispherical ends. Below are two cylinders, B B, of smaller diameter, which are called *heaters*, and which are connected with the boiler by two strong tubes. The object of these heaters is to expose a greater surface to be heated. They are full of water, as also are the tubes which connect them with the boiler, which is only half full.

The feed-water, sent by the pump, Q (fig. 292), reaches the boiler by a pipe, *n* (fig. 297), which passes to the bottom to prevent cold water from condensing steam ; a second pipe, *m*, leads the steam to the valve-chest. In the middle of the boiler is an oval hole, called a *manhole*, the object of which is to allow workmen to enter the boiler when it needs repairs. This hole, as well as two front ones, B B, of the heaters, is closed by what is called an *autoclave*. Here the cover, instead of being on the outside, is on the inside. A screw, T, fixed to this cover makes it press against the sides ; and as the pressure of the steam acts in the same direction, the greater the pressure the more tightly is the vessel closed.

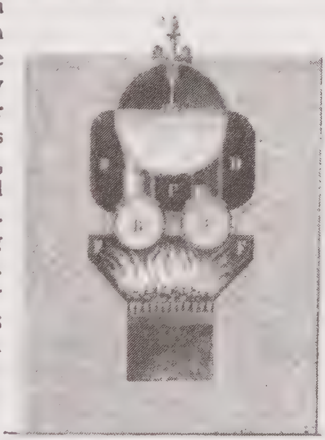


Fig. 298.

The furnace in which the boiler is placed is so constructed as to cause the heat to act upon a large surface, and to render the combustion as complete as possible. The products of combustion pass into tall chimneys, which from their great height increase the draught and thereby promote combustion.

288. **Float.**—This is a small apparatus, the object of which is to show the level of water in the boiler. It consists of a lever,

at one end of which is a piece of stone, F′, and at the other a counterpoise, *a* (fig. 297). The mass F′ weighs more than the counterpoise *a* ; but, as it is immersed in water, and thus loses part of its weight (106), it is in equilibrium, and the lever is horizontal so long as the level of water is at the desired height. But it sinks when there is too little water, and rises in the contrary direction when there is too much. Guided by these indications, the stoker can regulate the supply of water.

289. **Safety-valve.**—The pressure of steam in the boiler is measured by means of the manometer (145). But this instrument would not prevent explosions if its indications were neglected. Hence safety-valves are placed on boilers similar to that which Papin adopted in his digester (264). Fig. 299 represents on a larger scale one of these valves. It consists of a metal stopper, *c*, closing a tubulure, A, fixed on the boiler. To prevent this from sticking to the sides, the metal stopper is hollowed on three sides, as seen at S. It thus more resembles a clack-valve than an ordinary stopper. On the piece rests a movable lever, *ab*, loaded with a weight, *p*. By moving this along the lever the load on the valve can be modified at will. For this purpose marks are placed which indicate the position of the load corresponding to given pressures. Thus, suppose it is desired that the pressure shall not exceed five atmospheres, the weight is placed at the division 5 on the lever. Then, as long as the pressure is less than five, the safety-valve remains closed ; but if the pressure exceeds this amount the valve opens and gives exit to the steam, thus preventing an explosion. This arrangement of safety-valve is replaced in modern boilers by a strong spiral spring placed over the valve and keeping it in place. The tension of this spring is adjusted so that when the pressure of the steam exceeds a certain amount the spring is compressed and the valve rises, thus allowing the steam to escape.

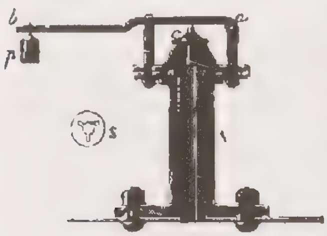


Fig. 299.

290. **Safety-whistle.**—This is another safety apparatus, which indicates at a distance when the level of water in the boiler is too low. It consists of a float, F (fig. 300), supported by a level, *ih*,

which moves about the joint *c*; a counterpoise, *p*, balances the float, and a small conical stopper, *a*, fixed to the lever, closes a tubulure on the boiler. This tubulure is closed at the top by two hollow hemispheres. In the centre of the lower one is a disc, which does not quite reach the edges. Between the two hemispheres is a circular interval, through which vapour escapes when the cone *a* does not close the tubulure.

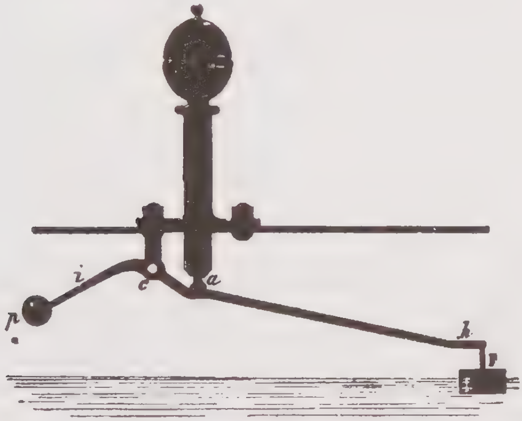


Fig. 300.

As long as the water is at the right height the float F is raised, and presses the cone against the tubulure; but if the level sinks, the float sinks, and with it the cone. The steam escapes round the disc *e*, and gives a very acute sound in striking against the edges of the upper hemisphere, which are bevelled. The system constitutes, in fact, a short stopped organ-pipe, yielding therefore a very acute sound (202).

On locomotives a similar whistle enables the driver to signal at a great distance by opening a stopcock, which allows the steam to escape.

CHAPTER XI

HYGROMETRY

291. **Hygrometry.**—The province of *hygrometry* is to determine the quantity of aqueous vapour or moisture contained in a given volume of air. The quantity is very variable; the atmosphere can scarcely ever be said to be completely saturated with vapour, even in our climate. Nor is it ever completely dry; for if *hygroscopic substances*—that is to say, substances with a great affinity for water, such as calcium chloride, sulphuric acid, quicklime, etc.—be at any time exposed to the air, they absorb more or less aqueous vapour.

The humidity does not depend on the absolute quantity of aqueous vapour present in the air, but on the greater or less distance of the temperature of the air from that at which the vapour would be saturated. Thus, if a cubic yard of air contains 150 grains of moisture, this weight represents the *absolute* quantity of water vapour present; if the air is at a temperature of 20° C., the quantity of moisture it could contain in a state of saturation is 204 grains; the ratio of these two quantities, $\frac{150}{204} = 0{\cdot}735$, represents the *relative* humidity or the *hygrometric state*. Under these circumstances we should say that the air is nearly three-quarters saturated. When the air is cold, it may be moist with very little vapour, and, on the contrary, when it is warm, it may be very dry, even with a large quantity of vapour. In summer the air usually contains more aqueous vapour than in winter, notwithstanding which it is less moist, because as the temperature is higher the vapour is farther from its point of saturation. When a room is warmed, the quantity of moisture is not diminished, but the humidity of the air is lessened, because its point of saturation is raised (265). The air may thus become so dry as to be injurious to health, and accordingly vessels of water are frequently placed on the stoves used for heating a room.

The quantity of vapour contained in the air varies greatly with

the seasons, the climate, the temperature, and various local causes. A mean degree of moisture is best suited to the animal economy. In a state of great dryness—as in the case, for instance, during the prevalence of north-east winds—the transpiration through the skin is too abundant; the skin dries up and chaps, and general discomfort ensues. In an atmosphere which is too moist, transpiration is slower, and a feeling of depression and heaviness is felt. Hence it is necessary to regulate in a suitable manner the moisture of dwelling-rooms, so as to avoid these two extremes.

292. **Hygroscopes.**—There are two classes of instruments by which the hygrometric state of the air may be ascertained. One class, called *hygroscopes*, simply tell whether the air is more or less moist, but give no indications as to the quantity of moisture it contains; others, called *hygrometers*, enable us to measure it with some accuracy.

All substances which absorb aqueous vapour, like common salt and many others known as *deliquescent salts*, may serve as hygroscopes. This is also the case with a great number of animal and vegetable substances, such as paper, parchment, whalebone, hair, catgut, etc., which lengthen as the air becomes moist, but contract as it becomes dry, and thus give an indication of the greater or less quantity of vapour in the air. The spiral awns of certain geraniums which unroll in moist air may serve as hygroscopes.


Fig. 301.

A branch of pine which has been peeled, and the stouter end of which is fixed in a wall, indicates changes in the moisture of the air by its greater or less curvature.

A great number of instruments have been constructed on this principle which serve as *hygroscopes*. One, which is sometimes useful, is the *hair* or *Saussure's hygroscope*. It consists of a brass frame (fig. 301), on which is fixed a hair, *c*, fastened at the top in a clamp, *a*. The lower part of the hair passes round a pulley, *o*, and supports a small weight, *p*. To the pulley is attached an index which moves over a graduated scale. When the humidity of the air increases, the hair becomes longer and the point of the index moves down. With a drier atmosphere the hair shortens and the point rises.

To this class of hygroscopes belong the chimney ornaments, one of the most common forms of which is that of a small male and female figure, so arranged in reference to a little house, with two doors, that when it is moist the man goes out, and the woman goes in, and *vice versâ* when it is fine. They are founded on the property which twisted strings or pieces of catgut possess of untwisting when moist, and of twisting when dry.

As these hygroscopes only change slowly, their indications are always behindhand with the state of the weather; nor are they, moreover, very exact.

293. **Hygrometers.**—The most exact of all hygrometers is the *chemical hygrometer*. This consists essentially of an arrangement by which a measured volume of air is passed through a series of drying tubes—that is, tubes containing some hygroscopic substance, such as calcium chloride, or pumice saturated with sulphuric acid. These tubes, having been previously weighed, are weighed again after the operation; an increase of weight is observed, which is due to the moisture absorbed by the hygroscopic substance, and this increase represents the weight of the moisture in the volume of air taken.

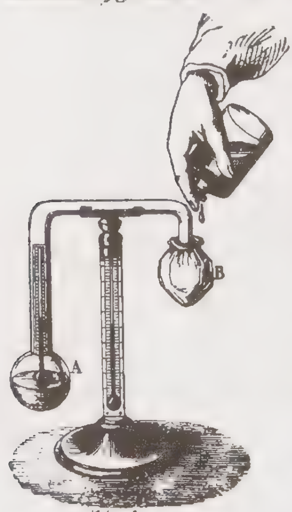


Fig. 302.

This method is very exact, but it is both difficult and tedious of execution.

More convenient than the above are what are called *condensation hygrometers*, in which the vapour of the atmosphere is made to condense on a body artificially cooled. This may be illustrated by having a small cup of polished metal in which are placed some water, a lump of ice, and a delicate thermometer. When the vessel gradually cools in a moist atmosphere, the layer of air in immediate contact with it cools also, and a point is ultimately reached at which the vapour present is just sufficient to saturate the air: the least diminution of temperature then causes a precipitation of moisture on the cup in the form of dew.

When the temperature rises again, the dew disappears, and the mean of the temperatures of appearance and disappearance is taken as the *dew-point.* The hygrometer of Dines is based on this principle.

A good example of an instrument of this class is met with in *Daniell's hygrometer*. This consists of two glass bulbs at the extremities of a glass tube bent twice (fig. 302). The bulb A is two-thirds full of ether, and a very delicate thermometer dips in it; the rest of the space contains nothing but the vapour of ether, the ether having been boiled before the bulb B was sealed. The bulb B is covered with muslin, and ether is dropped upon it. The ether in evaporating cools the bulb, and the vapour contained in it is condensed. The internal pressure being thus diminished, the ether in A forms vapours which condense in the other bulb B. In proportion as ether distils from the lower to the upper bulb, the ether in A becomes colder, and ultimately the temperature of the air in immediate contact with A sinks to that point at which its vapour is just more than sufficient to saturate it, and the excess is accordingly deposited on the outside as a ring of dew corresponding to the surface of the ether. The temperature at which this occurs is noted by means of the thermometer in the inside. The addition of ether to the bulb B is then discontinued, the temperature of A rises, and the temperature at which the dew disappears is noted. In order to render the deposition of dew more perceptible, the bulb A is made of black glass.

Fig. 303.

These two temperatures having been determined, their mean is taken as that of the dew-point. The temperature of air at the time of the experiment is indicated by the thermometer on the stem. The vapour pressure, f, corresponding to the temperature of the dew-point, is then found in the table of pressures (265). This pressure is exactly that of the vapour present in the air at the time of the experiment. The pressure, F, of vapour saturated at the temperature of the atmosphere is found by means of the same table; the quotient, obtained by dividing f by F, represents the hygrometric state of the air. For instance, the temperature of the air being 15°, suppose the dew-point is 5°. From this table

the corresponding pressures are $f = 6{\cdot}53$ millimetres, and $F = 12{\cdot}70$ millimetres ; hence, the hygrometric state $= f/F = 0{\cdot}514$.

A very convenient form of hygrometer, and one the use of which is rapidly extending, is that known as the *psychrometer* or *wet-bulb hygrometer*, which is based on the principle that a moistened body evaporates in the air more rapidly in proportion as the air is drier (260), and, in consequence of this evaporation, the temperature of the body sinks. The application of the principle to this purpose was first suggested by Leslie. The form of the apparatus usually adopted in this country is due to Mason. It consists of two delicate thermometers placed on a wooden stand (fig. 303). One of the bulbs is covered with muslin, and is kept continually moist by being connected with a reservoir of water by means of a string. Unless the air is saturated with moisture, the wet-bulb thermometer always indicates a lower temperature than the other, and the difference between the indications of the two thermometers is greater in proportion as the air is drier.

According to Glaisher, the temperature of the dew-point may be obtained by multiplying the *difference* between the temperatures of the wet and dry bulbs by a factor which depends on the temperature of the air at the time of observation, and subtracting the product thus obtained from this last-named temperature. The following are the numbers :—

Dry-bulb temperature F.°	Factor	Dry-bulb temperature F.°	Factor
Below 24°	8·5	34 to 35°	2·6
24 to 25	7·3	35—40	2·5
25—26	6·4	40—45	2·3
26—27	6·1	45—50	2·1
27—28	5·9	50—55	2·0
28—29	5·7	55—60	1·8
29—30	5·0	60—65	1·8
30—31	4·6	65—70	1·7
31—32	3·6	70—75	1·5
32—33	3·1	75—80	1·3
33—34	2·8	80—85	1·0

These are often known as *Glaisher's factors*. The temperatures are expressed on the Fahrenheit scale. As an example : if the temperature of the wet bulb is 49° and that of the dry bulb 54°, then the dew-point is 44°—that is, at this temperature the moisture present in the atmosphere would be just sufficient to saturate it.

CHAPTER XII

METEOROLOGICAL PHENOMENA WHICH DEPEND UPON HEAT

294. **Meteorology.**—Meteorology is that branch of physics which is concerned with the phenomena which occur in the atmosphere—such, for instance, as variations in the temperature and pressure of the air, wind, rain, storms, electric phenomena, etc.

295. **Mean temperature.**—The *mean daily temperature*, or simply *temperature*, is that obtained by adding together 24 hourly observations and dividing by 24. A very close approximation to the mean temperature is obtained by taking the mean of the highest and lowest temperatures of the day and of the night, which are determined by means of maximum and minimum thermometers (221). These ought to be protected from the sun's rays, raised above the ground, and be far from all objects which might influence them by their radiation. The lowest mean daily temperature is at 4 A.M., and the highest at 2 P.M.

The *temperature of a month* is the mean of those of 30 days, and the *temperature of a year* is the mean of those of 12 months. The highest mean monthly temperature is in July, and the lowest in January. The temperature of a place is the mean of its annual temperature for a great series of years. The mean temperature of London is 10·35° C., or 50·63° F. The temperatures in all cases are those of the air a few feet from the ground, and not those of the ground itself.

296. **Causes which modify the temperature of the air.**—The principal causes which modify the temperature of the air are the latitude of a place, its height—that is, its distance above sea level—the direction of the wind, and the proximity of seas.

Influence of the latitude. The temperature of the air and of the ground diminishes from the equator towards the poles. This is due to the fact that the sun's rays, which are vertical at the equator, are more and more inclined as we come nearer the poles. Now, the more acute is the angle under which the rays of heat fall

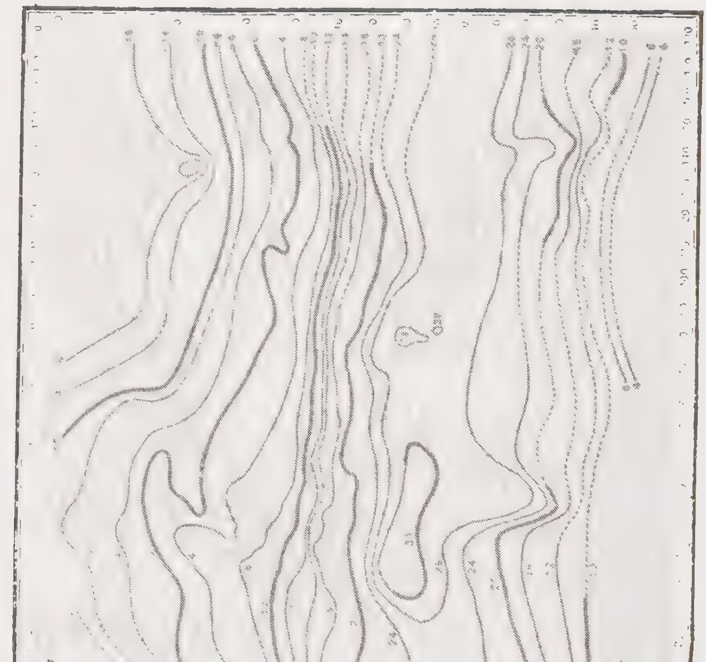
upon a body, the less is the body heated ; hence the heat absorbed decreases from the equator to the poles. Yet, as in summer the days are longer as we get nearer the north, the loss due to the increasing obliquity of the sun is partially compensated by the sun remaining longer above the horizon. Under the equator, where the length of the days is constant, the temperature is almost invariable ; in the latitude of London, and the more northerly countries, where the days are very unequal, the temperature varies greatly ; in summer it sometimes rises almost as high as under the equator. The lowering of the temperature produced by the change in latitude alone is small ; thus, at a distance of 115 miles north of London the average temperature is only 1° C. lower.

Influence of height. The height of a place above the sea level has a much more considerable influence on the temperature than its latitude. In the temperate zone an ascent of 540 feet corresponds to a diminution in the average temperature of 1° C.

The cooling as we ascend in the atmosphere has been observed in balloon ascents, and a further proof of it is seen in the perpetual snows which cover high mountains, even in the torrid zone. The height at which snow remains unmelted through the year, which is known as the *snow line*, or *line of perpetual snow*, differs in different places. On the Andes it commences at a height of 14,760 feet, on the Alps at 8,880 feet, and in Iceland at 3,070 feet.

Direction of winds. As winds share the temperature of the countries which they have traversed, their direction exercises great influence on the temperature in any place. In our climate the hottest winds are the south, then come the south-east, the south-west, the west, the east, the north-west, north, and, lastly, the north-east, which is the coldest. The character of the wind changes with the seasons : in continental Europe the east wind, which is cold in winter, is hot in summer.

Proximity of sea. The neighbourhood of the sea tends to render the temperature of the air uniform, by warming it in winter and cooling it in summer. The average temperature of the sea in equatorial and polar countries is always different from that of the atmosphere. With reference to the uniformity of the temperature, it has been found that in temperate regions—that is, from 25 to 50 degrees of latitude—the difference between the maximum and minimum temperature of a day does not exceed, on the sea, 2° to



3° C., while upon land it amounts to 12° to 15°. In islands the uniformity of temperature is maintained, even during the periods of greatest heat. In continents, on the contrary, the winters for the same latitudes become colder, and the difference between the temperatures of summer and winter becomes greater.

297. **Gulf Stream.**—A similar influence to that of the winds is exerted by currents of warm water. The mildness of the climate in the north-west of Europe is usually assigned to one of these—the Gulf Stream. This great body of water, taking its origin in equatorial regions, flows through the Gulf of Mexico, whence it derives its name; passing by the southern shores of North America, it makes its way in a north-easterly direction across the Atlantic, and finally washes the coast of Ireland and the north-west of Europe generally. It traverses 3,000 miles in about seventy-eight days. Its temperature in the Gulf is about 28° C., and is generally a little more than 5° C. higher than the rest of the ocean, on which it floats owing to its lower specific gravity. To its influence is due the milder climate of western Europe as compared with that of the opposite coast of America; thus, the River Hudson, which is in the same latitude as Rome, is frozen during three months in the year. It also causes the polar regions to be separated from the coast of Europe by a girdle of open sea; and hence the harbour of Hammerfest in 70° north latitude is open the year round. Besides its influence in thus moderating climate, the Gulf Stream is an important help to navigators.

298. **Isothermal lines.**—When all the points on a map whose temperature is known to be the same are joined, curves are obtained which Humboldt first described, and which he called *isothermal lines*. If the temperature of a place only varied with the obliquity of the sun's rays—that is, with the latitude—isothermal lines would all be parallel to the equator; but as the temperature is influenced by many local causes, especially by the height above the sea level and the distribution of land and water, the isothermal lines are always more or less curved. On the sea, however, they are almost parallel. A distinction is made between *isothermal lines*, *isotheral lines*, and *isochimenal lines*, where the *mean general*, the *mean summer*, and the *mean winter* temperatures are respectively meant. The maps facing pages 350, 352, and 354 represent these sets of lines respectively. An *isothermal zone* is the space comprised between two isothermal lines.

299. **Climate.**—By the *climate* of a place are understood the

whole of the meteorological conditions to which a place is subjected, its mean annual temperature, summer and winter temperatures, and the extremes within which these are comprised. Some writers distinguish seven classes of climate according to their mean annual temperature—a *hot climate*, from 30° to 25° C.; a *warm climate*, from 25° to 20° C.; a *mild climate*, from 20° to 15° C.; a *temperate climate*, from 15° to 10° C.; a *cold climate*, from 10° to 5° C.; a *very cold climate*, from 5° to zero; and an *arctic climate*, where the temperature is below zero.

Those climates, again, are classed as *constant climates*, such as the Havannah and Quito, where the difference between the mean summer and winter temperatures does not exceed 6° to 8°. In the Canary Islands the mean summer temperature is 23°·4 and that of winter 18°, so that the difference is less than 6°. *Variable climates*, such as those of Paris and London, where the difference amounts to from 16° to 20°; and *extreme climates*, such as those of Pekin and New York, where the difference is much greater. Island climates are generally but little variable, as the temperature of the sea varies little; and hence there is a great difference between a *land* and a *sea* climate (296). The former is characterised by a greater range of temperature than the latter. Thus the difference between the mean temperatures of summer and winter is 11° at Cherbourg, 15° at Paris, and 20° at Vienna, although they differ little in latitude. In the north-east of Ireland ice scarcely forms in winter, and the myrtle flourishes as in Portugal; yet Ireland is in the same latitude as Königsberg in Prussia, where the mean annual temperature is 5° C., the range being from $-3°\cdot5$, the mean monthly temperature in January, to 13°·6, that of July. Winter in Plymouth is not colder than in Florence or Montpellier, yet grapes do not flourish there in the open air; for while they can stand a somewhat severe cold in winter, they require a hot summer to become ripe. In Irkutsk in Siberia, where the ground is constantly frozen at a depth of three feet, oats and rye can be grown, for the short but hot summer is sufficient to ripen them; while in Iceland, where the mean annual temperature is much higher, and the cold in winter is inconsiderable, no cereals can be grown, for the low summer temperature is insufficient to bring them to maturity.

The reason of this is that the land absorbs and radiates heat easily; it thus becomes more easily heated and more rapidly cooled than the sea, which, mainly from its great specific heat (276),

ISOTHERMS FOR JANUARY.

is not so rapidly heated, but, on the other hand, does not part so soon again with the heat it has acquired.

Again, part of the heat which falls on the sea is consumed in forming vapour on the surface.

But the temperature is by no means the only characteristic which influences the climate of a place ; there is, in addition, the influence of aqueous vapour in the air in the neighbourhood of seas, and particularly that of clouds, which are more frequent near coasts ; they temper the ardour of the sun by day, and diminish the loss of heat which the earth experiences by radiation at night. To these climatic influences must be added the quantity and frequency of rain, the number of storms, the direction and intensity of the winds, and the nature of the soil.

300. **Fogs and mists.**—When aqueous vapour, rising from a vessel of boiling water, diffuses in the colder air, it is condensed ; a sort of cloud is formed, which consists of a number of minute droplets of water, which remain suspended in the air. These are usually spoken of as vapour, yet they are not so, at any rate not in the physical sense of the word ; they are, in reality, condensed vapour, but, from the minute weight of the individual particles in comparison with their great surface, they cannot overcome the comparatively great resistance of the air,sink very slowly, and are even driven upwards by the lightest current of air.

When this condensation of aqueous vapour is not produced by contact with cold solid bodies, but takes place throughout large regions of the atmosphere, the effect is to form *fogs* or *mists*, which in fact are nothing more than the appearance seen over a vessel of hot water.

A chief cause of fog consists in the moist ground being at a higher temperatare than the air. Such fogs are of frequent occurrence in autumn. The vapours which then rise, condense and become visible. In all cases, however, the air must have reached its point of saturation before condensation takes place. Fogs are also produced when a current of hot and moist air passes over land or water at a lower temperature than its own, for then, the air being cooled, as soon as it is saturated, the excess of vapour present is condensed. In this way are formed the *winter fogs*.

The distinction between mists and fogs is one of degree rather than of kind. A fog is a very thick mist.

When water is coated with a layer of coal-tar, it is prevented from evaporating. Frankland ascribed the *dry fog* met with in

London to the large quantities of coal-tar and paraffine vapour which are sent into the atmosphere, and which, condensing on the particles of fog, prevent their evaporation.

Aitkin has shown that aqueous vapour never condenses unless some liquid or solid is present on which it is deposited. Particles of dust in the air which are always present though invisible are the nuclei for clouds and fogs. This he showed by passing steam into air which had been filtered by passing through cotton wool; it remained quite clear, while a turbidity was produced under the same circumstances in unfiltered air. The density of the cloud was found to depend on the number of particles of dust in the air. A most abundant source of dust is the combustion of coal. The sulphur in the coal in burning also forms sulphurous acid, which, though a gas, is found to act as a nucleus, as in its formation it probably carries with it some excessively minute particles of unburnt sulphur.

301. **Clouds.**—*Clouds* are masses of vapour condensed into water particles of extreme minuteness, like fogs and mists, from which they differ only in occupying the higher regions of the atmosphere; they always result from the condensation of vapour which rises from the earth or the sea. There is no essential difference between a fog and a cloud; a cloud is a fog at a great height; a fog is a cloud low down or on the ground. An observer in a valley sees the peak of a mountain enclosed by a cloud, while one on the summit sees himself surrounded by a fog. According to their appearance, they have been divided by Howard into four principal kinds: the *nimbus*, the *stratus*, the *cumulus*, and the *cirrus*. These four kinds are represented in fig. 304, and are designated respectively by one, two, three, or four birds on the wing.

The *cirrus* consists of small whitish clouds, which have a fibrous or wispy appearance. The name of *mares'-tails*, by which they are generally known, well describes their appearance. Of all clouds these are the highest, for they present the same appearance on the tops of high mountains as they do in valleys. Their height has been determined at about 27,000 feet. From the low temperature of the spaces which they occupy, it is more than probable that cirrus clouds consist of frozen particles; and hence it is that halos, coronæ, and other optical appearances, produced by refraction and reflection from ice-crystals, appear almost always in these clouds and their derivatives, more particularly cirro-stratus. Their appearance often precedes a change of weather.

ISOTHERMS FOR JULY.

Cumulus clouds are rounded forms which look like mountains, piled one on another, and are also known as *woolpack cloud.* They are more frequent in summer than in winter, and, after being formed in the morning, they generally disappear towards evening. If, on the contrary, they become more numerous, and especially if surmounted by cirrus clouds, rain or storms may be expected. Their height varies from 4,450 to 5,190 feet.

Stratus clouds consist of very large and continuous horizontal sheets, which chiefly form at sunset, and disappear at sunrise. They

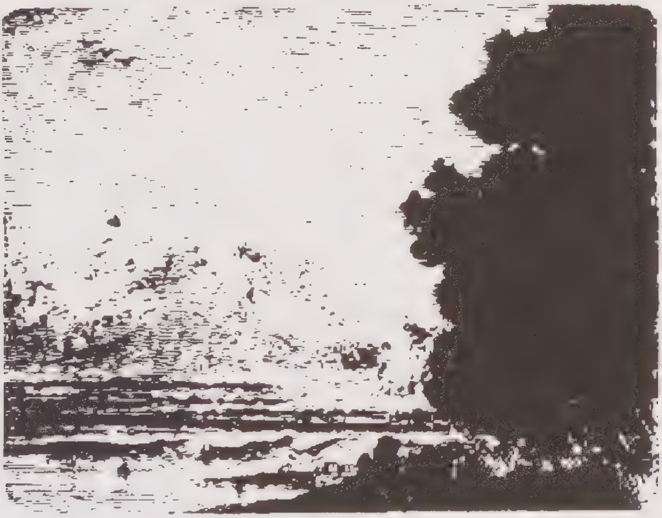


Fig 304.

are frequent in autumn and unusual in springtime, and are lower than the preceding. The height is about 680 yards. The stratus is generally a fine-weather cloud.

The *nimbus* or rain clouds, which are sometimes classed as one of the fundamental varieties, are properly a combination of the three preceding kinds. They affect no particular form, and are solely distinguished by a uniform grey tint and by fringed edges. They are indicated on the right of the figure by the presence of one bird. Their height varies from about 3,600 to 7,000 feet.

The fundamental forms pass into one another in the most varied

manner; Howard has classed these transitional forms as *cirro-cumulus*, *cirro-stratus*, and *cumulo-stratus*, and it is often very difficult to tell, from the appearance of a cloud, which type it most resembles. The cirro-cumulus is most characteristically known as a 'mackerel sky;' it consists of small roundish masses, disposed with more or less regularity and connection. It is frequent in summer, and attendant on warm and dry weather. *Cirro-stratus* appears to result from the subsidence of the fibres of cirrus to a horizontal position, at the same time that they approach each other laterally. The form and relative position when seen in the distance frequently give the idea of shoals of fish. The tendency of *cumulo-stratus* is to spread, settle down into the *nimbus*, and finally fall as rain.

The height of clouds varies greatly, being much higher in summer than winter. Gay-Lussac, in his balloon ascent, at a height of 23,000 feet observed cirrus clouds above him, which appeared still to be at a considerable height. In Ethiopia M. d'Abbadie observed storm clouds whose height was only 690 feet above the ground.

In order to explain the suspension of clouds in the atmosphere Halley supposed that clouds are formed of an infinity of extremely minute vesicles, hollow, like soap-bubbles, filled with air which is hotter than the surrounding air; so that these vesicles float in the air like so many minute balloons. At present it is held that clouds and fogs consist of extremely minute droplets of water, which are retained in the atmosphere by the ascensional force of currents of hot air, just as light powders are raised by the wind. Ordinarily, clouds do not appear to descend, but this absence of downward motion is only apparent. In fact, clouds do usually fall slowly, but then the lower part is continually dissipated on coming in contact with the lower and more heated layers: at the same time the upper part is always increasing from the condensation of new vapours, so that from these two actions clouds appear to retain the same height. A cloud, indeed, is not something fixed and unchanging; it exists only in its formation and in its cessation; it is not a product but a process. At night when there are no ascending currents the clouds do seem to fall.

302. **Formation of clouds.**—Many causes may concur in the formation of clouds.

i. The low temperature of the higher regions of the atmosphere. For, owing to the solar radiation, vapour is continually being dis-

engaged from the earth and from water, and from its small density rises in the atmosphere ; meeting there continually colder and colder layers of air, it becomes saturated, and then, condensing in extremely minute droplets, gives rise to clouds.

ii. The hot and moist currents of air rising during the day undergo a gradually lower pressure, and in expanding are cooled and the water vapour they carry with them is condensed. Hence it is that high mountains, arresting the currents of air, and forcing them to rise, are an abundant source of rain.

This is well seen in Portugal, where the south-west winds of the west of Europe are forced upward by the Sierra d'Estrella, so that at Coimbra on the windward side the rainfall (303) is 119 inches, while in the region of the Tagus it is 16 inches.

iii. A hot, moist current of air mixing with a cold current undergoes a cooling, which brings about a condensation of the vapour. Thus the hot and moist winds of the south and south-west, mixing with the colder air of our latitudes, gives rain. The winds of the north and north-east tend also, in mixing with our atmosphere, to condense the vapours ; but as these winds, owing to their low temperature, are very dry, the mixture rarely attains saturation, and generally gives no rain.

303. **Rain.**—When the individual vapour particles become larger and heavier by the constant condensation of aqueous vapour, and when finally individual particles unite, they form regular drops, which fall as *rain*. At great heights raindrops are very small, but they become larger as they fall, for, from their low temperature, they condense on their surface the aqueous vapour of the layers of air through which they fall. The quantity of rain which falls annually in any given place, or the annual rainfall, is measured by means of a *rain-gauge* or *pluviometer*.

The simplest form of rain-gauge consists of a funnel (fig. 305) which has a certain definite area, 12 square inches for example, and which fits in a bottle. The rain which falls on this area is collected in the bottle, and the quantity which has fallen during the period of observation is measured by means of a graduated glass. Thus, if in 24 hours the quantity collected measures 2·3 fluid ounces, that is, 4 cubic inches, and if the area of the funnel is 12 inches, this represents a rainfall of one-third of an inch in 24 hours. The funnel and bottle are usually enclosed in a metal cylinder which is taller than the funnel, so as to retain any snow which may fall.

Many local circumstances may affect the quantity of rain which falls in different countries: but, other things being equal, most rain falls in hot climates, for there the evaporation is most abundant. The rainfall decreases, in fact, from the equator to the poles. At London the annual rainfall is 23·5 inches; at Bordeaux it is 25·8; at Madeira it is 27·7; at Havannah it is 91·2; and at St. Domingo it is 107·6. The quantity varies with the seasons; in Paris, in winter it is 4·2 inches; in spring, 6·9; in summer, 6·3; and in autumn, 4·8 inches. The heaviest annual rainfall at any place on the globe is on the Khasi Hills in Bengal, where it is 600 inches; of which 500 inches fall in seven months. On July 1, 1851, a rainfall of 25½ inches on one day was observed at Cherrapoonjee. At Kurachee, in the north-west of India, the rainfall is only 7 inches.

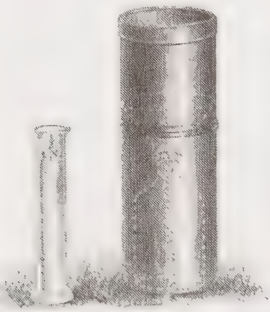


Fig. 305.

Under similar conditions the quantity of rain diminishes with the distance from the sea. Thus, if the annual rainfall is 1 in the centre of Germany, it is 1·2 in the centre of England and 1·75 on the English coasts. The rainfall increases with the height above the sea level, for mountains produce rain when they arrest a current of moist air (300).

The driest place in England is Lincoln, with a rainfall of 20 inches, and the wettest Styehead Pass in Cumberland, where the rainfall is 165 inches.

An inch of rain on a square yard of surface represents 46·8 pounds, or 4·68 gallons. On an acre it corresponds to 22,900 gallons, or 101 tons. 100 *tons per inch per acre* is a ready way of remembering this.

304. **Dew. Hoar frost.**—*Dew* is merely aqueous vapour which has condensed on bodies during the night in the form of minute globules. It is occasioned by the chilling which bodies near the surface of the earth experience in consequence of the radiation at night. Their temperature having then sunk several degrees below that of the air, it frequently happens, especially in hot seasons, that this temperature is below that at which the atmosphere is saturated. The layer of air which is immediately in contact with

the chilled bodies, and which has virtually the same temperature, then deposits a portion of the vapour which it contains, just as when a bottle of cold water is brought into a warm room it becomes covered with moisture, owing to the condensation of aqueous vapour upon it.

According to this explanation, which was first given by Dr. Wells in 1812, all causes which promote the cooling of bodies increase the quantity of dew. These causes are the emissive power of bodies, the state of the sky, and the agitation of the air. Bodies which have a great radiating power become cool more readily, and therefore ought to condense more vapour. In fact, there is generally no deposit of dew on metals, whose radiating power is very small, especially when they are polished; while the ground, sand, glass, and plants, which have a great radiating power, become abundantly covered with dew. On some plants, for instance, not merely are droplets of dew formed, but regular layers of water.

The state of the sky also exercises a great influence on the formation of dew. If the sky is cloudless, the planetary spaces send to the earth an inappreciable quantity of heat, while the earth radiates very considerably, and therefore, becoming very much chilled, there is an abundant deposit of dew. But if there are clouds, as their temperature is far higher than that of the planetary spaces, they radiate in turn towards the earth, and, as bodies on the surface of the earth only experience a feeble chilling, no deposit of dew takes place.

Wind also influences the quantity of vapour deposited. If it is feeble, it increases it, inasmuch as it renews the air; if it is strong, it diminishes it, as it heats the bodies by contact, and thus it does not allow the air time to become cooled. Finally, the deposit of dew is more abundant according as the air is moister, for then it is nearer its point of saturation.

In those countries of the hot zones which are near the sea, dew may replace rain, as in Peru and Chili; in the interior of great continents it is infrequent. In England, in the course of the year, it is equivalent to 1½ inch of rainfall.

We must distinguish between the dew formed in consequence of lowering of temperature by radiation, and the deposit formed by warm moist air passing over a cold wall; in mild weather this deposit forms a liquid, and in severe weather a snowy or icy coating. A deposit of this kind is most abundantly found on good conductors, as they carry away the heat fastest.

Hoar frost and *rime* are nothing more than dew which has been deposited on bodies cooled below zero, and has therefore become frozen. The flocculent form which the small crystals present of which rime is formed shows that the vapours solidify directly without passing through the liquid state. Hoar frost, like dew, is formed on bodies which radiate most, such as the stalks and leaves of vegetables, and is chiefly deposited on the parts turned towards the sky.

305. **Snow. Sleet.**—*Snow* is water solidified in stellate crystals variously modified, and floating in the atmosphere. These crystals arise from the congelation of the minute particles which constitute

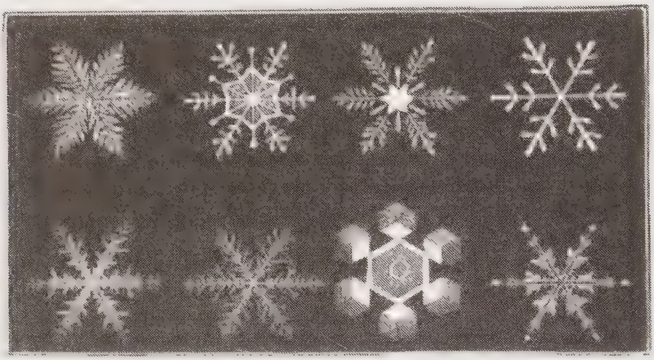


Fig. 306.

the clouds, when the temperature of the latter is below zero. They are more regular when formed in a calm atmosphere. Their form may be investigated by collecting them on a black surface, and viewing them through a strong lens. They exhibit exquisite regularity and at the same time variety of form. Fig. 306 shows some of the forms as seen through a microscope from the observations of Dr. Glaisher.

It snows most in countries near the poles, or in such as are high above the sea level. Towards the poles, the earth is constantly covered with snow; the same is the case on high mountains, where there are perpetual snows even in equatorial countries.

One *foot* of snow may, with sufficient accuracy, be taken as equal to one *inch* of rain.

Sleet is also solidified water, and consists of small icy needles aggregated together in a confused manner. Its formation is ascribed to the sudden congelation of the minute globules of the clouds in an agitated atmosphere.

When in consequence of severe frost the ground is cooled below zero, and a thaw sets in, the moist air passing over the ground deposits its moisture, which is converted into a continuous sheet of ice ; this is known as *glazed frost* (the French *verglas*) ; it may also occur when raindrops which have been cooled below zero in the higher regions of the air, and are accordingly in a state of superfusion, fall on the ground which may even be above the freezing-point.

306. **Hail.**—*Hail* consists of masses of compact ice of different sizes, which fall in the atmosphere. In our climate hail falls principally during spring and summer, and at the hottest times of the day ; it rarely falls at night. The fall of hail is always preceded by a peculiar noise. Hail is generally the precursor of rain storms ; it seldom accompanies them, and follows them more rarely still, especially if the rain has lasted for some time. Hail clouds seem generally to be very low. The regions in which a hail storm occurs form in most cases a long narrow strip. A hailstone, fig. 307, consists of a core of compressed snow, which is surrounded by concentric layers of ice. Hailstones fall from the size of small peas to that of a sphere two inches in diameter. Their temperature is from $-0{\cdot}5^{\circ}$ to -4° C. The formation of hail, and more especially the great size of hailstones, have never been altogether satisfactorily accounted for. While snow sometimes falls for days together, hail storms seldom last longer than a quarter of an hour, and they are also far less frequent. Hail is always accompanied by some electrical disturbance in the atmosphere.

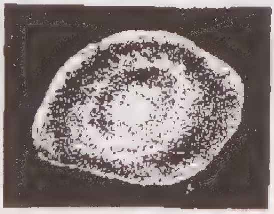


Fig. 307.

307. **Direction and velocity of winds.**—*Winds* are currents moving in the atmosphere with variable directions and velocities.

The direction of the wind is determined by means of vanes, and its velocity by means of the *anemometer*. There are several forms

of this instrument. The most usual consists of a small vane with fans, which the wind turns; the velocity is deduced from the number of turns made in a given time, which is measured by means of an endless screw and wheelwork. That most commonly used in this country, and represented in fig. 308, is known as *Robinson's anemometer.* It consists of a metal cross with hemispherical cups at the ends, and fixed to an axis. The motion of this cross is transmitted by means of an endless screw to a train of wheelwork; and from the number of turns made in a given time, which is indicated by the pointers, the velocity of the wind is deduced. In our

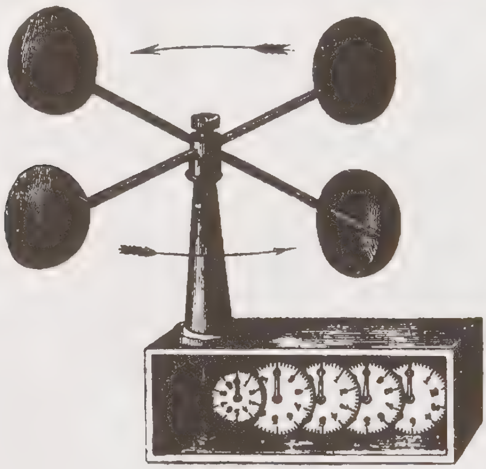


Fig. 308.

climate the mean velocity is from 18 to 20 feet in a second. With a velocity of 6 or 7 feet, the wind is moderate; with 30 or 35 feet, it is fresh; with 60 or 70 feet, it is strong; with a velocity of 85 to 90 feet, it is a tempest, and from 90 to 120 it is a hurricane. The velocity of a wind may, under appropriate circumstances, be measured by observing the time which the shadow of a cloud takes to pass over a field, or any space the dimensions of which are known.

308. **Causes of winds.**—Winds are produced by a disturbance of the equilibrium in some parts of the atmosphere—a disturbance always resulting from a difference in temperature between adjacent

countries. Thus if the temperature of a certain extent of ground becomes higher, the air in contact with it becomes heated, it expands, and rises towards the higher regions of the atmosphere; whence it flows, producing upper currents which blow from hot to cold countries. But at the same time the equilibrium is destroyed at the surface of the earth, for the barometric pressure on the colder adjacent parts is greater than on that which has been heated, and hence a current will be produced with a velocity dependent on the difference between these pressures; thus two distinct winds will be produced, an upper one setting *outwards* from the heated region, and a lower one setting *inwards* towards it.

309. **Regular, periodic, and variable winds.**—According to the more or less constant directions in which winds blow, they may be classed as regular, periodic, and variable.

i. *Regular winds* are those which blow all the year through in a virtually constant direction. These winds, which are also known as the *trade winds*, are, far from the land in equatorial regions, observed to blow uninterruptedly from the north-east to the south-west in the Northern Hemisphere, and from the south-east to the north-west in the Southern Hemisphere. They prevail on the two sides of the equator as far as 30° of latitude, and they blow in the same direction as the apparent motion of the sun; that is, from east to west.

The air above the equator, being gradually heated, rises as the sun passes round from east to west, and its place is supplied by the colder air from the north or south. The direction of the wind, however, is modified by this fact: that the velocity which this colder air has derived from the rotation of the earth—namely, the velocity of the surface of the earth at that point from which it started—is less than the velocity of the surface of the earth at the point at which it has now arrived; hence the currents acquire, in reference to the equator, the constant directions stated above.

ii. *Periodic winds* are those which blow regularly in the same direction, at the same seasons, and at the same hours of the day; the monsoon, simoom, and the land and sea breeze are examples of this class. The name *monsoon* is given to winds which blow for six months in one direction, and for six months in another. They are principally observed in the Red Sea and in the Arabian Gulf, in the Bay of Bengal, and in the Chinese Sea. These winds blow towards the continents in summer, and in a contrary direction in winter. The *simoom* is a hot wind which blows over the

deserts of Asia and Africa, and is characterised by its high temperature and by the sands which it raises in the atmosphere and carries along with it. During the prevalence of this wind the air is darkened, the skin feels dry, the respiration is accelerated, and a burning thirst is experienced.

This wind is known under the name of *sirocco* in Italy and Algiers, where it blows from the great desert of Sahara. During its prevalence people remain at home, the windows and doors being carefully closed. In Egypt, where it prevails from the end of April to June, it is called *kamsin*, from a word signifying *fifty* ; for it lasts ordinarily 50 days ; 25 before the spring equinox, and 25 after. When caravans are surprised by this wind, men cover their faces with thick cloths and camels turn their back to the torment. The natives of Africa, in order to protect themselves from the effects of the too rapid perspiration occasioned by this wind, cover themselves with fatty substances.

The *land and sea breeze* is a wind which blows on the sea coast during the day from the sea towards the land, and during the night from the land to the sea. For during the day the land becomes more heated than the sea, in consequence of its lower specific heat (276) and its greater conductivity, and hence, as the air above the land becomes more heated than that over the sea, it ascends and is replaced by a current of colder and denser air flowing from the sea towards the land. During the night the land cools more rapidly than the sea, and thus the same phenomenon is produced, but in the opposite direction. The sea breeze commences after sunrise, increases to three o'clock in the afternoon, decreases towards evening, and is changed into the land breeze after sunset. These winds are only perceived at a slight distance from the shores. They are regular in the tropics, but less so in our climate ; and traces of them are seen as far as the coasts of Greenland. They are even observed on the shores of such inland lakes as that of Constance ; and still more markedly in the great American lakes. The proximity of mountains also gives rise to periodic daily breezes. In like manner the open country is warmer during the day than an adjacent forest, while the reverse is the case at night. Hence at night there is a slight breeze from the forest towards the open, and during the day from the open country towards the forest.

iii. *Variable winds* are those which blow sometimes in one direction and sometimes in another, without being subject to any

law. In mean latitudes the direction of the winds is very variable; towards the poles this irregularity increases, and under the arctic zone the winds frequently blow from several points of the horizon at once. On the other hand, in approaching the torrid zone they become more regular. The south-west wind prevails in the north of France, in England, and in Germany; in the south of France the direction inclines towards the north, and in Spain and Italy the north wind predominates.

310. **Law of the rotation of winds.**—Notwithstanding the great irregularity which characterises the direction of the winds in our latitudes, it has been ascertained that the wind has a preponderating tendency to veer round according to the sun's motion; that is, to pass from north, through north-east, east, south-east, to south, and so on round in the same direction from west to north: that it often makes a complete circuit in that direction, or more than one in succession, occupying many days in doing so, but that it rarely veers and very rarely or never makes a complete circuit in the opposite direction. For a station in south latitudes a contrary law of rotation prevails.

This law, though more or less suspected for a long time, was first formally enunciated and explained by Dove, and is known as *Dove's law of the rotation of winds.*

311. **Weather charts.**—A considerable advance has been made in weather forecasts by the frequent and systematic publication of *weather charts*; that is to say, maps in which the barometric pressure, the temperature, the force of the wind, etc., are expressed for considerable areas in an exact and comprehensive manner. A careful study of such maps renders possible a forecast of the weather for a day or more in advance. We can here do little more than explain the meaning of the principal terms in use.

If lines are drawn through those places on the earth's surface where the corrected barometric height at a given time is the same, such lines are called *isobarometric* lines, or, more briefly, *isobaric* lines, or *isobars*. Between any two points on the same isobar there is no difference of pressure. Isobars are usually drawn for a difference of $\frac{1}{10}$ of an inch.

Suppose A and B to be points on two isobars, the pressure being greater at A than at B. If A B be joined, and a line, A C, be drawn perpendicular to A B and of such a length as to represent on any suitable scale the difference in pressure between the two places, the steepness of the line C B, or the ratio of C A to A B,

is a measure of the fall in pressure between the two stations, and is called the *barometric gradient*. Gradients are usually expressed in England and America in hundredths of an inch of mercury for one degree of sixty nautical miles, and on the Continent in millimetres for the same distance. The closer are the isobars the steeper is the gradient, and the more powerful the wind; and though no exact numerical relationship can be proved to exist between the steepness of the gradient and the force of the wind, it may be mentioned that a gradient of about 6 represents a strong breeze; and a gradient of 10, or a difference in pressure of $\frac{1}{10}$ of an inch for 60 miles, is a stiff gale.

The direction of the wind is from the place of higher pressure to that of lower, and in reference to this the law of Buys Ballot may be mentioned, which has been found to hold in all cases in the Northern Hemisphere, where local configuration does not come too much into play. *If we stand with our back to the wind the line of lower pressure is on the left hand.* For places in the Southern Hemisphere exactly the opposite law holds.

If within any area the pressure is lower than outside it, the wind blows round that area, the place of lowest pressure being on the left. The direction of the wind is, in short, the opposite of that of the hands of a watch. Such a circulation is called *cyclonic*; it is that which is characteristic of the West Indian hurricanes, which are known as *cyclones*. Conversely the wind blows round an area of higher pressure in the same direction as the hands of a watch; and this circulation is called *anticyclonic*.

Cyclonic systems are by far the most frequent, and are characterised by steep gradients; the air in them tends to move in towards the centre, and thence to the upper regions of the atmosphere. They bring with them, over the greater part of the region which they cover, much moisture, an abundance of cloud, and heavy rain. Anticyclonic systems have the opposite characteristics; the gradients are slight, and the wind is light. The air is dry, so that there is but little cloud, and no rain. Cyclonic systems, from the dampness of the air, produce warm weather in winter, and cold wet weather in summer. Anticyclonic systems bring our hardest frosts in winter and greatest heat in summer, as there is but little moisture in the air to temper the extremes of climate. Both systems travel over the earth's surface, the cyclones rapidly, the anticyclones more slowly.

CHAPTER XIII

SOURCES OF HEAT AND COLD

312. **Different sources of heat.**—The following different sources of heat may be distinguished : i. the *mechanical sources*, comprising friction, percussion, and pressure ; ii. the *physical sources*—that is, solar radiation, terrestrial heat, molecular actions, changes of condition and electricity ; iii. the *chemical sources*, or molecular combinations, and more especially combustion.

MECHANICAL SOURCES

313. **Heat due to friction.**—The friction of two substances, one against the other, produces heat, which is greater the greater the pressure and the more rapid the motion. For example, the axles of carriage wheels, by their friction against the boxes, often become so strongly heated as to set fire to *wood* in contact with them, as, for instance, the nave. By rubbing together two pieces of ice in an

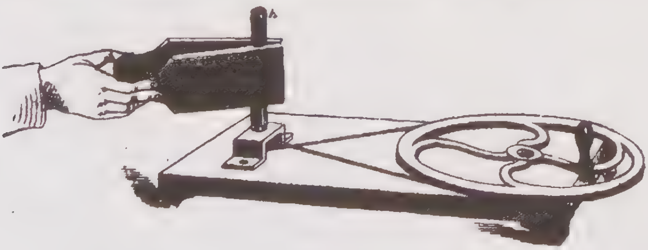


Fig. 309.

exhausted receiver at a temperature below zero, Sir H. Davy partially melted them. In boring a brass cannon, Rumford found that the heat developed in the course of 2½ hours was sufficient to raise 26½ pounds of water from the freezing to the boiling point.

This may be well illustrated by an experiment (fig. 309) devised by Tyndall. A brass tube, *b*, closed at the bottom, about 4 inches long and less than an inch in diameter, fits on the whirling table (33), having been three-quarters filled with cold water, and corked. If now it be clasped by a sort of wooden squeezer in which there are two semicircular grooves, and then be made to rotate, the heat developed by the friction is sufficient to boil the water and expel the cork by which it is closed. This experiment is easier to perform with alcohol, which has a smaller specific heat and a lower boiling-point than water.

The ignition of a lucifer match ; the increased temperature observed in the tools which have been used for sawing, for boring, for filing, and the like ; the warmth produced by rubbing the hands together, are all instances of the production of heat by friction.

An iron drag is known to have become so heated that water hissed when dropped on it ; to the heat produced in friction are due the hot bearings of railway carriages, the temperature of which is sometimes sufficiently high to set fire to them.

Shooting stars, too, are probably small planetary bodies which get within the sphere of the attraction of the earth, and in falling towards it are raised to incandescence by friction against the atmosphere, and by the heat produced by the compression of the air.

314. **Heat due to pressure and percussion.**—If a body be compressed, its temperature rises as the volume diminishes. In solids and liquids, which are but little compressible, the disengagement of heat is not great, though Joule verified it in the case of water and of oil, which were exposed to pressures of 15 to 25 atmospheres. Similarly, when weights are laid on metal pillars, heat is evolved, and is absorbed when they are removed.

The production of heat by the compression of gases is easily shown by means of the *pneumatic syringe* (fig. 310). This consists of a glass tube with thick sides, closed hermetically by a leather piston. At the bottom of the piston there is a cavity, in which a small piece of tinder is placed. The tube being full of air, the piston is suddenly plunged downwards ; the air thus compressed disengages sufficient heat to ignite the tinder, which is seen to burn when the piston is rapidly withdrawn. The inflammation of the tinder in this experiment indicates a temperature of at least 300°. At the moment of compression a bright flash is observed, which was originally attributed to the high temperature of the air ; but

it is simply due to the combustion of the oil which greases the piston.

Percussion is also a source of heat, as is observed in the sparks which are thrown off by horses in trotting over a hard pavement

Fig. 310.

or over a flinty road, and in striking steel against a flint. In firing a shot at an iron target, a sheet of flame is frequently seen at the moment of impact. A small piece of iron hammered on an anvil becomes very hot, and it is stated that in this way a skilful blacksmith can raise a piece of iron to redness.

315. **Mechanical equivalent of heat.**—These experiments and numerous others show that there is an intimate connection between motion and heat. Whenever the motion of a body is stopped, whether suddenly, as by impact, or gradually, as in the case of friction, there is in all cases a disengagement of heat; the motion of the mass is transformed into a motion of the ultimate particles or molecules of which the body is made up, and the energy of this motion is what constitutes heat (211). In like manner, whenever work is done a quantity of heat is expended; the most striking example of this is the steam-engine, where the heat produced by the burning of the coal is transformed into the motion of the engine itself, and of the machinery which it drives. If we compare the quantity of heat which is produced by burning a certain weight of combustible with the heat which leaves the engine in the condensing water (282), and make allowance for loss by radiation and conduction, there is a deficit which is represented by a transformation of a certain portion of the heat into work.

Not only can it be shown experimentally that there is such a transformation, but it has been established beyond the shadow of a doubt that there is a definite numerical relation between the two; this is one of the greatest scientific achievements of the nineteenth

century, and has led to the most important consequences. The honour of this magnificent discovery is due to Mayer in Germany and to Joule in England, and it is the experimental researches of the latter that first fully established the law. The simplest of his experiments was made by means of a brass vessel, B (fig. 311), provided with a brass paddle-wheel (indicated by the dotted lines), which could be made to rotate about a vertical axis. The water was prevented from being whirled round by fixed obstructions, through which, however, the paddles could pass. Two weights, E and F, were attached to cords which passed over the pulleys, C and D, and were connected with the axis A. These weights in falling cause the wheel to rotate. The height of the fall, which

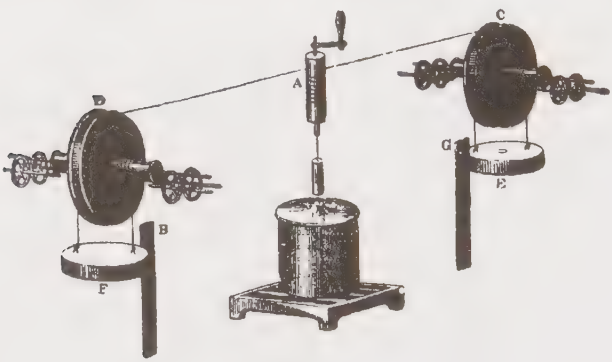


Fig. 311.

in Joule's experiments was about 63 feet, was indicated on the scales G and H.

The roller A was so constructed that by detaching a pin the weight could be raised without moving the wheel. The vessel B, containing a definite weight of water at a known temperature, was placed on a stand and the weights allowed to sink. When they had reached the ground, the roller was detached from the axis, and the weights again raised, the same operations being repeated twenty times. As the weight was allowed to fall, it put the paddle in motion, and the friction against the water thus produced raised its temperature. Knowing the weight of the water and the rise of temperature, and making certain necessary corrections, it was

easy to deduce the quantity of heat produced by the friction of the paddles in consequence of a given weight falling through a known height.

Experiments have been made by other methods, and the general result arrived at is that the amount of work required to raise a weight of one pound through 1,400 feet, or, what is the same thing, 1,400 pounds through one foot, or 1,400 *foot-pounds*, is equivalent to the amount of heat required to raise one pound of water through one degree *Centigrade* or one thermal unit.

This number is called the *mechanical equivalent of heat* ; it is really the expression in terms of mechanical units (foot-pounds) of the equivalent of one thermal heat unit (one pound-degree Centigrade of heat). It is commonly known as *Joule's equivalent*, and denoted by the letter J. In French books the reciprocal of J is often employed, that is, the *thermal equivalent of the unit of work*.

The principle that there is an invariable ratio in which work is transformed into heat, and, conversely, in which heat is transformed into work, is known as the principle of the *equivalence of heat and work*.

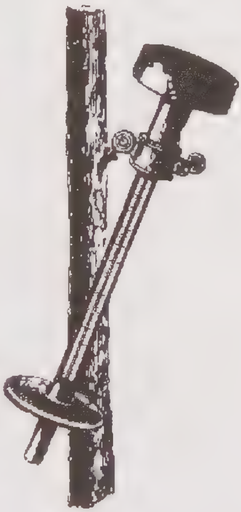


Fig. 312.

316. **Solar radiation.** — The most powerful of all sources of heat is the sun.

Various attempts have been made to determine the quantity of heat which the sun emits. Pouillet invented an apparatus which he called a *pyrheliometer* (fig. 312). It consists of a flat metal cylinder or box, containing mercury. In this is introduced the bulb of a thermometer, the stem of which is protected by a piece of brass tubing. By means of a collar and screw, the instrument may be attached to a stake. The face of the cylinder, which is turned to the sun, is coated with lamp-black ; a disc is fixed to the stem, the object of which is to insure that the sun's rays fall perpendicularly on the blackened face of the cylinder ; this is attained by turning the instrument so that the shadow of the cylinder exactly covers the disc. From observations made with this apparatus, Pouillet

calculated that if the total quantity of heat which the earth receives from the sun in the course of a year were employed to melt ice, it would be capable of melting a layer of ice all round the earth of 35 yards in thickness. But simple calculation shows that from the surface which the earth exposes to the solar radiation and from the distance which separates the earth from the sun, the quantity of heat which the earth receives is less than one part in two thousand millions of the total heat emitted by the sun.

317. **Terrestrial heat.**—Our globe possesses a heat peculiar to it, which is called *terrestrial heat.* The temperature of the earth below the surface of the ground varies with the seasons down to a certain depth, at which it remains constant in all seasons. It is hence concluded that the sun's heat does not penetrate below a certain internal layer, which is called the *layer of constant temperature.* The depth of this layer below the earth's surface varies, of course, in different parts of the globe: at Paris it is about 30 yards, and the temperature is constant at 11·8° C.

Below the layer of constant temperature, the temperature is observed to increase, on the average, 1° C. for every 90 feet. This increase has been verified in mines and artesian wells (103). According to this, at a depth of 3,000 yards, the temperature of the corresponding layer would be 100°, and at a depth of 20 to 30 miles there would be a temperature sufficient to melt all substances which exist on the surface. Hot springs and volcanoes confirm the existence of this central heat.

In the Mont Cenis tunnel, observations at a point in the interior, over which was a mass of rock 5,080 feet in thickness, showed an increase of 1° for 164 feet.

Since the temperature decreases from the interior to the exterior, there must be a constant loss from the surface. Owing to the low conducting power of the earth, this cooling is very slow; it has been estimated that the cooling due to this cause would not amount to 1° in a million years.

318. **Chemical combination. Combustion.**—Whenever two bodies unite, in virtue of their reciprocal affinity, this operation is known as the act of *chemical combination.* Chemical combinations are usually accompanied by a certain elevation of temperature. When these combinations take place slowly—as when iron oxidises in the air, and produces rust—the heat produced is imperceptible; but if they take place rapidly, the disengagement of heat may be very intense. The same quantity of heat is produced in both cases,

but when evolved slowly it is dissipated as fast as it is formed, and no increase of temperature can be perceived.

Combustion is chemical combination attended with the disengagement of light and heat. In the ordinary combustion in lamps, fires, candle, etc., the carbon and hydrogen of the coal or of the oil combine with the oxygen of the air, giving rise to aqueous vapour, carbonic acid, and other volatile products which are given off as smoke. The old expression that *fire destroys everything* is incorrect. It destroys nothing: it simply puts certain elements at liberty to unite with others: it *decomposes*, but at the same time *produces*. A body in being burned is transformed, but its substance is not destroyed.

Many combustibles burn with flame. A *flame* is a gas or vapour raised to a high temperature by combustion. Its illuminating power varies with the nature of the products formed. The presence of a solid body in the flame increases the illuminating power. The flames of hydrogen and carbonic oxide gases and of alcohol are pale; they only contain gaseous products of combustion. But the flames of candles, lamps, and coal gas have a high illuminating power. They owe this to the fact that the high temperature produced decomposes certain of the gases with the production of carbon, which, not being perfectly oxidised, becomes white-hot in the flame. Coal gas, when burnt in an arrangement by which it obtains an adequate supply of air, as in Bunsen's burner, is almost entirely devoid of luminosity, though its temperature is very high, being about 1,300° C. A non-luminous flame may be made luminous by placing in it platinum wire or asbestos fibre (232). The illuminating power of a flame does not depend solely on its temperature. A hydrogen flame, which is the palest of all flames, has a very high temperature.

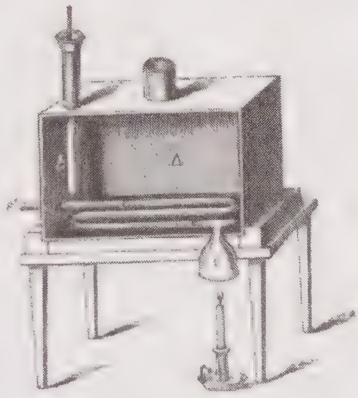


Fig. 313.

319. **Rumford's calorimeter.**—In order to determine the amount

of heat which is produced by combustion, Rumford used the calorimeter depicted in fig. 313. A metal box, A, contains a known weight of water at a known temperature; through it passes a copper worm tube, *s s'*, which is open at one end, *s'*, and terminates at the other end in a funnel, *c*. The substance whose heating effect is to be determined is placed underneath the funnel, and, having been previously weighed, is burned. The gaseous products of combustion pass then through the worm, and, imparting their heat to the water, raise the temperature. From the weight of the water and its increase in temperature, which is measured by the thermometer, *t*, and from the weight of the body burned, its heating effect may be determined.

By experiments with more perfect arrangements, based, however, on the same general principle, the heating effect of the following substances has been determined. The numbers represent the *thermal units*—that is, pounds of water which are raised through 1° C. by the combustion of a pound of the substance, and are called the *thermal equivalents.*

Hydrogen	34,500	Phosphorus	5,700
Marsh gas	13,060	Dry turf	4,800
Petroleum	12,300	Carbon bisulphide	3,400
Olive oil	9,860	Wood	2,900
Anthracite	8,460	Carbonic oxide	2,400
Charcoal	8,080	Sulphur	2,200
Tallow	8,000	Zinc	1,300
Alcohol	7,180	Iron	1,181
Coal	7,000	Copper	600

From the above result it follows that a pound of coal would raise from the ordinary temperature and completely evaporate about 11 pounds of water (276). In practice, however, the best coal and the most convenient heating arrangements do not give more than two-thirds of this result.

320. **Various sources of cold.**—Besides the cold (i.e. absorption of heat) caused by the passage of a body from the solid to the liquid state, of which we have already spoken (250), cold is produced by the expansion of gases, by radiation in general, and more especially by radiation at night.

321. **Cold produced by the expansion of gases.**—We have seen that when a gas is compressed its temperature rises. The reverse of this is also the case; when a gas is rarefied a reduction of tem-

perature ensues, the heat lost being due to the work done against external pressure by the expansion. This may be shown by placing a delicate spiral thermometer (fig. 258) under the receiver of an air-pump, and exhausting; at each stroke of the piston the needle moves in the direction of zero, and regains its original position when air is admitted.

The machines now in use for the manufacture of ice depend on this property of gases. The heat developed by the compression of air is removed by a current of cold water; a series of tubes containing the air thus compressed and cooled being placed in brine, the air is allowed to expand; in so doing it cools the brine so considerably as to freeze water contained in vessels placed in the brine. Instead of atmospheric air, Pictet uses sulphurous acid, and Linde ammonia, for the artificial production of cold. It may be stated that by the most improved methods a ton of coals (used in working a steam-engine by which the compression is effected) can produce ten tons of ice.

The principle is also applied in the construction of *refrigerating-rooms*. The air is compressed by what is in effect a steam-condensing pump (154), and is then reduced to the temperature of the atmosphere by a current of cold water. Being next allowed to expand, the air is greatly cooled, and is made to pass into the spaces where temperature is to be reduced. By this means it is not difficult to reduce the air to a temperature 15° or more below zero. Such rooms are used for storing meat in hot weather, and also in transporting whole carcases of meat from abroad, and the principle is also applied in cooling in breweries, where the temperature of fermentation has to be kept within definite limits.

322. **Cold produced by radiation at night.**—During the day, the ground receives from the sun more heat than it radiates into space, and the temperature rises. The reverse is the case at night. The heat which the earth loses by radiation is no longer compensated for and consequently a fall of temperature takes place, which is greater according as the sky is clearer, for clouds send towards the earth more heat rays than come from the celestial spaces. In some winters it has been found that rivers have not frozen, the sky having been cloudy, although the thermometer has been for several days below $-4°$; while in other less severe winters the rivers freeze when the sky is clear. The emissive power exercises a great influence on the cold produced by radiation; the greater it is, the greater is the cold.

In Bengal, the cooling at night is used in manufacturing ice (269). It is said that the Peruvians, in order to preserve the shoots of young plants from freezing, light great fires in their neighbourhood, the smoke of which, producing an artificial cloud, hinders the cooling produced by radiation.

Country people are in the habit of saying that it freezes more when the moon appears than when it is hidden by clouds. They are right in this; but the freezing is not, as they think, due to the influence of the moon. It is owing to the absence of clouds.

BOOK VI

ON LIGHT

CHAPTER I

TRANSMISSION, VELOCITY, AND INTENSITY OF LIGHT

323. **Theories of Light.**—*Light* is the agent which, by its action on the retina, excites in us the sensation of vision. That part of physics which deals with the properties of light is known as *optics*.

In order to explain the origin and transmission of light, various hypotheses have been made, the most important of which are the *emission* or *corpuscular* theory, and the *undulatory* theory.

The emission theory assumes that luminous bodies emit particles or corpuscles of matter of extreme tenuity and without weight. These travel in straight lines with enormous velocity. Penetrating into the eye they strike the retina and produce the sensation which constitutes vision. According to this theory, then, light is imponderable matter which is shot out from a luminous body as a bullet is shot from a gun, and is capable of penetrating glass and other transparent media without leaving any trace behind it. This is the theory that was held by Newton, and it was chiefly through his influence that it so long remained the accepted creed.

On the *undulatory* theory all bodies, as well as the celestial spaces, are filled by an extremely subtle elastic medium, which is called the *luminiferous ether*. The luminosity of a body is due to an extremely rapid vibratory motion of its molecules, which, when communicated to the ether, is propagated in all directions in the form of spherical waves; and this vibratory motion, being thus transmitted to the retina, calls forth the sensation of vision. The vibrations of the ether take place not in the direction in which the wave is travelling, but at right angles to this direction. They are

transverse vibrations, and are thus to be distinguished from the longitudinal vibrations of the air particles in the transmission of sound-waves through air (171). A good idea of what takes place in the case of the propagation of light-waves is obtained by considering the concentric waves produced on the surface of still water when a stone is dropped in. The water particles move up and down but do not travel away. It is the *wave form* which spreads out in all directions.

The luminiferous ether penetrates all bodies ; it occupies the celestial spaces, and, although it presents no appreciable resistance to the motion of the denser bodies, it is possible that it hinders the motion of the smaller comets. It has been found, for example, that Encke's comet, whose period of revolution is about $3\frac{1}{4}$ years, has its period diminished by about 0·11 of a day at each successive rotation, and this diminution is ascribed by some to the resistance of the ether.

The fundamental principles of the undulatory theory were enunciated by Huyghens, and advocated by Young, who showed how a large number of optical phenomena, particularly those of diffraction, were to be explained by that theory. Subsequently, too, though independently of Young, Fresnel showed that the phenomena of diffraction, and also those of polarisation, are explicable on the same theory, which, since his time, has been generally accepted.

The undulatory theory not only explains the phenomena of light, but it reveals an intimate connection between these phenomena and those of heat ; it brings out also many analogies between the phenomena of light and those of sound, regard being had to the differences of the media by which light and sound are propagated.

324. **Various sources of light.**—The various sources of light are the sun, the stars, heat, chemical combination, phosphorescence, electricity, and meteoric phenomena.

The origin of the light emitted by the sun and by the stars is unknown ; it is assumed by some that the ignited envelope by which the sun is surrounded is gaseous, and at a very high temperature.

As regards the light developed by heat, experiment has shown that bodies begin to be luminous in the dark at a temperature of about 500° ; above that the light is brighter in proportion as the temperature is higher.

The luminous effects observed in many chemical combinations are due to the high temperatures produced. This is the case with the artificial lights used for illuminations; for luminous flames are essentially gaseous masses containing solids heated to incandescence (318).

Phosphorescence is the property which a large number of substances possess of emitting light under certain conditions. It is observed in living animals, of which the best-known case is that of the *glow-worm*; here it is very intense, and the brightness seems to depend on the will. Its light consists of a continuous spectrum from C to near *h*, and is particularly rich in blue and green rays. In tropical climates the sea is often covered with a bright phosphorescent light due to myriads of small luminous infusoria (*Noctiluca miliaris*).

Langley showed that in ordinary oil or gas flames more than 97·6 per cent. of the total energy is expended as heat, and is useless as regards light; and in sources at a high temperature, such as the arc and incandescent electric light, the proportion, although less, is still considerable.

The light of the firefly (*Pyrophorus noctilucus*), which is found abundantly in Cuba, when examined by the spectroscope and bolometer is found to be devoid of red and infra-red rays—that is, to contain only luminous rays. It thus represents an economical form of light. As the more refrangible rays are those which affect the eye, it is desirable to obtain in our artificial lights as great a proportion of the energy in this form as possible, and it is in this direction that improvement in illumination is to be looked for.

Phosphorescence cannot be due to a high temperature, for substances show it which are decomposed at such a temperature.

Decaying wood, and some kinds of fish in a state of putrefaction, also exhibit this phenomenon. Certain substances, like some varieties of fluor-spar, become phosphorescent by friction; while others, such as the sulphides of calcium, barium, and strontium, become luminous in the dark by having been previously exposed to the sun's rays.

Balmain's *luminous paint* depends on this property. Its principal ingredient is the phosphorescent calcium sulphide.

Nöggerath observed that agates, in the operation of polishing, often emitted a bright phosphorescent red light, which gave them the appearance of red-hot iron, and yet the increase of temperature was not more than 12° to 15° C.

325. **Opaque, transparent, translucent bodies. Absorption of light.**—Bodies on which light falls give rise to two distinct effects: one class, such as wood, metals, most stones, completely stop its passage through them; while others, such as air and glass, allow light to pass. The first class of bodies comprehends those which are called *opaque*, and the second the *transparent* and *translucent* bodies. The term transparent or *diaphanous* is applied to all bodies which transmit light, and through which objects can be distinctly seen; while *translucency* is usually restricted to the case of bodies through which objects cannot be distinctly seen. Polished glass may be called either transparent or diaphanous; but ground glass, oiled paper, and thin porcelain are translucent, for, while they transmit light, objects cannot be distinguished through them.

Of all bodies which transmit light, none can be said to be perfectly transparent; all extinguish, or *absorb*, a portion of the light which impinges on them. Even atmospheric air, which is transparent in comparison with all liquids and solids known to us, is not perfectly transparent, as is shown by many phenomena of everyday occurrence. Distant objects appear under a smaller optical angle, their colour is duller, and the contrasts of light and shade are weaker; in short, the more distant an object, the more does it appear surrounded by an opalescent veil, as is more particularly visible on distant hills. This effect of imperfect transparency of the atmosphere is known as *aërial perspective*. Again, on the tops of high mountains, the number of stars visible to the naked eye is greater than in the plain, owing to the fact that in the former case the layer of air traversed is not so thick as in the latter case. In like manner, too, the sun appears less luminous when on the horizon, for then its rays pass through a thicker layer of air.

Just as there are no perfectly transparent substances, so, too, there are none which are quite opaque; at any rate, when the thickness is very small. Gold, which is one of the densest metals, allows an appreciable quantity of light to pass when it is beaten out in the form of fine leaf.

Foucault showed that, when the object-glass of a telescope is thinly silvered, the layer is so transparent that the sun can be viewed through it without danger to the eyes, since the metallic layer reflects the greater part of the heat and light; the tint appears slightly bluish, while in the case of gold it is greenish.

326. **Propagation of light.**—A *medium* is any space or substance which light can traverse, such as a vacuum, air, water, glass,

etc. A medium is said to be ***homogeneous*** when its chemical composition and density are the same in all parts; these are conditions which are independent of each other. The atmosphere, for instance, has everywhere the same composition; but not everywhere the same density, owing to the variations in pressure and temperature to which it is subject in various places.

Experiment shows that ***in every homogeneous medium light is propagated in a right line.*** For, if an opaque body is placed in the right line which joins the eye and the luminous body, the light is intercepted. In like manner, we cannot receive any impression of light through a series of holes in opaque plates superposed on each other, excepting when these holes are in a straight line. The light which passes into a dark room by a small aperture leaves a luminous trace, which is visible from the light falling on the dust particles suspended in the atmosphere.

Light emanates from luminous bodies in all directions, for we see them equally in all positions in which we are placed around them.

Light changes its direction on meeting an object which it cannot penetrate, or when it passes from one medium to another. These phenomena will be described under the heads *reflection* and *refraction*.

327. **Luminous ray and pencil.**—To this sending-out of light in all directions from a luminous body the same term, radiation, is applied, as in the case of heat; a *luminous ray*, or *ray of light*, is the line in which light is propagated; a *luminous pencil*, or *pencil of light*, is a collection of rays from the same source. It is said to be *parallel* when it is composed of parallel rays; *divergent*, when the rays separate from each other; and *convergent*, when they tend towards the same point. Examples of these will occur in the study of mirrors and of lenses.

328. **Shadow. Penumbra.**—When light falls upon an opaque body, it cannot penetrate into the space immediately behind the body, and this space is called the *shadow*.

In determining the extent and the shape of shadow projected by a body, two cases are to be distinguished: that in which the source of light is a single point, and that in which it is a body of any appreciable extent.

In the first case, let S (fig. 314) be the luminous point, and M a spherical body which causes the shadow. If an infinitely long straight line, SP, move round the sphere M, always passing

through the point S and touching the sphere, this line will describe a conical surface, which, beyond the sphere, separates that portion of space which is in shadow from that which is illuminated. In the present case, on placing behind the opaque body a screen, Q, the limit of the shadow, GH, will be sharply defined. This is not,

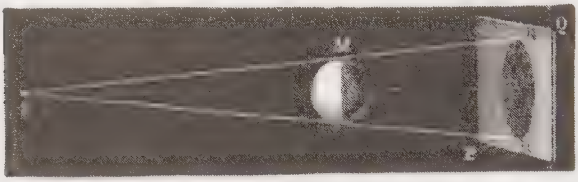


Fig. 314.

however, usually the case, for luminous bodies have always a certain magnitude, and are not mere luminous points ; the shadow formed by a luminous point is called the *geometrical shadow*.

In the second case, let L (fig. 315) be a luminous sphere, and let a straight line, AMG, be drawn touching the outside of this sphere and of the sphere M. Assuming that this line moves tan-

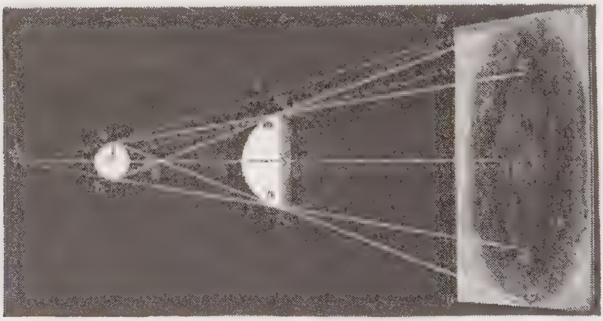


Fig. 315.

gentially round the two bodies, it will produce on the screen, P, a circle, GH, completely in darkness. If now a second straight line, SNC, be drawn tangentially on the inside of the two spheres, it will produce a cone, the summit of which is at B, and the base on the screen in the circle DC, which is greater than the circle GH.

The circular space between the two circumferences is neither entirely in the shadow nor entirely in the light, for it is only illuminated by a part of the body L ; whence arises the name *penumbra* (partial shadow). Under ordinary conditions, in which luminous bodies have a certain size, shadows are always surrounded by a penumbra. This decreases in intensity from the centre towards the edges ; it has a greater extent the nearer the source of light is to the body illuminated, and the more distant is the screen.

From these considerations it is to be explained why the shadow of a body exposed to the sun, when received close behind the body, is sharply defined, but at a greater distance is quite indistinct. Thus we cannot state the precise point where the shadow of a church spire ceases. In like manner, too, a hair which in sunlight is held close over a sheet of paper forms a sharp shadow, but if held a couple of inches above the paper no shadow can be perceived.

329. **Velocity of light**.—Light moves with such a velocity that at the surface of the earth there is, to ordinary observation, no

Fig. 316.

appreciable interval between the occurrence of any luminous phenomenon and its perception by the eye. And accordingly this velocity was first determined by means of astronomical observations. Römer, a Danish astronomer, in 1675, first deduced the velocity of light from observations of the eclipses of one of Jupiter's satellites.

Jupiter is a planet round which five *satellites* revolve, as the moon does round the earth. The second of these, *e* (fig. 316) (until the recent discovery of a satellite nearer to Jupiter than any of the others, this second was known as Jupiter's *first* satellite), *suffers occultation*—that is, passes into Jupiter's shadow—at equal

intervals of time, which are 42h. 28m. 36s. While the earth moves in that part of its orbit nearest Jupiter, its distance from that planet does not materially alter from day to day, and the successive occultations occur at the calculated times ; but in proportion as the earth moves away in its revolution round the sun, S, the discrepancy between the observed occultation and the calculated time of its occurrence increases ; and when, at the end of six months, the earth has passed from the position T to the position *t*, a *total* retardation of 16m. 36s. is observed between the time at which the phenomenon is seen and that at which it is calculated to take place. But when the earth was in the position T, the sun's light reflected from the satellite *e* had to traverse the distance *e*T ; while in the second position the light had to traverse the distance *et*. This distance exceeds the first by the quantity *t*T, for, from the great distance of the satellite *e*, the rays *et* and *e*T may be considered parallel. Consequently, light requires 16m. 36s. to travel the diameter *t*T of the terrestrial orbit, or twice the distance of the earth from the sun, which gives for its velocity 190,000 miles per second. This has been confirmed by the results of other experiments made by different methods ; the number now generally admitted is 186,000 miles per second, or 300,000 kilometres per second, or 877,000 times the velocity of sound (175).

To give some idea of this enormous velocity, it may be remarked that a cannon-ball with a velocity of 1,000 feet per second would require more than seventeen years to traverse the distance from the earth to the sun, while light requires only 8 minutes and 8 seconds.

The stars nearest the earth are separated from it by at least 206,265 times the distance of the sun. Consequently, the light which they send requires 3½ years to reach us. Those stars which are only visible by means of the telescope are possibly at such a distance that thousands of years would be required for their light to reach our planetary system. We may hence form an idea of the immensity of the heavens, and how small is our globe in comparison with this infinity.

330. **Intensity of light. Photometer.**—The intensity of a source of light—that is, the energy of its illuminating power—is measured by the quantity of light which it sends on a given surface at a given distance from the source ; for example, a screen a yard square. From the property which luminous rays have of diverging, the quantity of light falling on the screen, or its illumination, decreases

rapidly as the screen is removed from the luminous body. It may be shown, geometrically, that the illumination is inversely as *the square of the distance* of the screen from the source—that is, that when the distance of an illuminated body from the source of light is doubled, it receives one-fourth the amount of light ; at three times the distance, one-ninth ; and so forth. This law is only strictly true when the source of light is a point.

This law may be demonstrated by the aid of the apparatus called a *photometer*, from two Greek words which signify *measure of light*. One form consists of a ground-glass screen, fixed vertically on a wooden base (fig. 317). In front of this screen is an opaque rod, beyond which are the sources of light to be compared, placed in such a manner that the shadows of the rod cast by the two sources form

Fig. 317.

on the screen, the shadow due to each source being illuminated by the other source. Now, it will be observed that when the two sources have the same illuminating power, the depth of the shadows cast by the two is the same at the same distance ; but if one of the sources of light is more powerful than the other, the shadow due to the weaker source is more illuminated than the other ; and in order that the shadows may be of equal intensity, the more powerful light must be removed further away.

These details being premised, the law of the decrease of light may be demonstrated as follows :—In a dark room, a candle is placed at any distance from the photometer—a yard, for instance—and then, at double the distance, a lamp giving the same light as four of the same kind of candles is placed in the same line, in the direction

of the opaque rod. The two shadows on the screen will then be found to have exactly the same depth, the shadow cast by the candle being just as much illuminated by the lamp as that cast by the lamp is illuminated by the candle. Thus the screen receives as much light from the candle at one yard as it receives from the lamp (equal to four candles) at two yards. It may also be shown in the same manner that a lamp giving the same light as nine candles gives at three yards only the same illumination as one at one yard, and so forth, which proves the law.

It is important to observe that it is in consequence of the *divergence* (326) of luminous rays that light decreases as the distance increases. This decrease does not obtain in the case of parallel rays ; the illumination of a surface due to parallel rays would be the same at all distances, were it not for the absorption which takes place in even the most transparent media.

The light of the sun is 600,000 times as powerful as that of the moon, and 16,000,000,000 times as powerful as that of *α Centauri*, the third in brightness of all the stars. The moon is thus 27,000 times as bright as this star. The sun is 5,000 million times as bright as Jupiter, 20,000 million times as bright as Sirius, and 80 billion times as bright as Neptune. Its light is estimated to be equal to that of 5,500 wax candles at a distance of 1 foot. That of the full moon is about equal to that given by *one* wax candle at a distance of 126 inches. The more recent dynamo-electric machines can produce light equal to that of 100,000 standard candles.

331. **Bunsen's photometer.**—This depends on the following principle. If a grease-spot is made in a screen formed of a sheet of blotting-paper, and a source of light is looked at through the paper, the grease-spot will appear brighter than the rest of the paper. When the source is held in front, so that the screen is seen by reflected light, the grease-spot will appear darker than the rest of the paper. If now the screen is supported vertically, and the two sources, A and B, are placed one on each side of it, and their distances adjusted so that the grease-spot is neither brighter nor darker than the surrounding paper, it follows that the screen is receiving as much light from one as from the other source. When this is the case the illuminating powers of the two sources are directly as the squares of their distances from the paper.

This is the method in actual use for determining the illuminating powers of gas and other artificial lights. For this purpose a standard light is used ; in England this is that of a spermaceti

candle, *c*, $\frac{7}{8}$ of an inch in diameter, which burns 120 grains in an hour. The French standard of light is that of a *Carcel lamp*, which burns 607 grains pure colza oil in an hour with a flame 1·6 inch in height and gives a light equal to that of 9·5 English standard candles. This is fixed at one end of a graduated rule, *aa* (fig. 318), while at the other end is fixed a gas-jet, *g*, provided with a gas-meter, *m*, by which the quantity of gas can be regulated and measured. A paper screen, *b*, with the grease-spot, is fixed to a support which moves along the rule; this position is shown by the index, *i*, attached to the support. By trial a position is found for it at which the grease-spot just disappears; the paper is then equally illuminated on both sides, and it only remains to read off

Fig. 318.

the distances of the two lights, and make the calculation in the manner described above.

Thus the scale is divided into 100 parts, and suppose the screen is at 20 divisions from the standard candle when the grease-spot disappears, the gas being thus at a distance of 80 divisions—this being so, this particular gas-flame has sixteen times the illuminating power of the candle, and is spoken of as having a *sixteen-candle power*.

A fair degree of illumination in an ordinary room is that equivalent to the light of from 16 to 24 candles at a distance of a yard; while the light falling on a table should not be less than of 24 candles at this distance.

The intensity of light is measured photographically by an *actinometer*; this is an arrangement by which a strip of photographically sensitive paper can be exposed for any length of time

to the action of light; the time required for this paper to match a certain shade of colour is a measure of the intensity of the illumination.

The difficulty of obtaining candles which give a light sufficiently uniform for standard purposes has led Harcourt to adopt as unit the light formed by burning a mixture of 7 volumes of pentane gas and 20 volumes of air, at the rate of half a cubic-foot in an hour, in a specially constructed burner so as to produce a flame of constant height. This is known as the pentane standard, and has been found to answer well in practice.

CHAPTER II

REFLECTION OF LIGHT. MIRRORS.

332. When a pencil of rays falls on a bright polished surface, it bounds off from it, changing its direction, and this is spoken of as the *reflection* of light. The fact of this reflection, and the laws which govern it, may be investigated by the apparatus represented in fig. 319. It consists of a graduated circle in a vertical plane, supported on three levelling-screws. Two brass slides, I and K, move round the circumference. They support two small tubes, *i* and *c*, directed exactly towards the centre. On the slide I there is, moreover, a small mirror, M, which can be inclined at will. The zero of the graduation is at A, and extends to 90 degrees on each side.

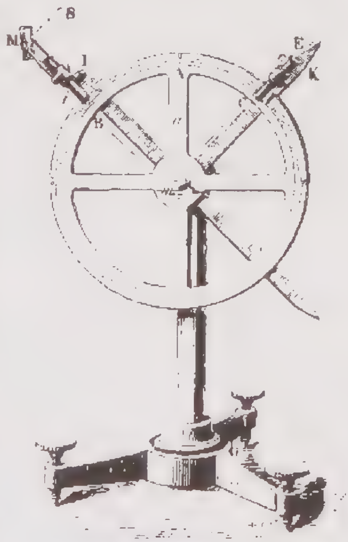


Fig. 319.

These details being known, the slide I having been more or less removed from zero, the mirror M is inclined so that a ray of light, S, after having been reflected on this mirror, shall pass through the tube *i* and fall upon a second mirror *m* arranged horizontally in the centre of the circle; there the ray of light is reflected a second time, and takes the direction *m*E. The slide K

is then moved to or from A, until, when the eye is placed at E, the reflected ray *m*E is seen through the tube *c*. If now the number of degrees contained in the arcs AB and AC be read off, they will be found to be exactly equal. The angle B*ma*, which the pencil B*m* makes with the perpendicular to the mirror *m*, is called the *angle of incidence*; and the angle C*ma* is called the *angle of reflection*. Hence, *the angle of reflection is equal to the angle of incidence.* In the construction of the apparatus, care is taken that the axes of the tubes *i* and *c* are in one and the same plane, parallel to that of the graduated circle, and therefore perpendicular to the surface of the small mirror *m*, and containing the normal, *ma*; and therefore *the incident and the reflected rays are both in the same plane, which is perpendicular to the reflecting surface.*

In the above drawing the direction in which light is propagated is represented by arrows; the same will be the case with all optical diagrams which we shall have occasion to introduce.

333. **The reflection of light is never complete.**—The light which falls upon a body is never completely reflected; a certain portion is always absorbed by the reflecting body. If we represent by 100 the quantity of incident light, the reflected portion may be 50, 80, 90, according to the nature and degree of polish of the reflecting body; but it will never amount to 100.

Thus, when light falls perpendicularly upon a body, the light which is reflected is $\frac{2}{3}$ of the incident light in the case of that reflected from a metal mirror, $\frac{3}{4}$ from mercury, $\frac{1}{25}$ from glass, and $\frac{1}{50}$ from water.

The best reflectors are polished metals, especially if they are white, like mercury and silver. Black bodies reflect no light. Translucent substances reflect a small quantity, and absorb more or less according to their thickness, while they transmit the remainder. This is what takes place with air, water, glass, and all transparent media.

For one and the same substance the quantity of reflected light increases not only with the degree of polish, but with the obliquity of the incident rays. For instance, if a sheet of white paper be placed before a candle, and be looked at very obliquely, an image of the flame is seen by reflection, which is not the case if the eye receives less oblique rays.

The intensity of the reflection varies with different bodies, even when the degree of polish and the angle of incidence are the same. It also varies with the nature of the medium which the light is

traversing before and after reflection. Polished glass immersed in water loses a great part of its reflecting power.

334. **Irregular reflection. Diffused or scattered light.**—The reflection from the surfaces of polished bodies, the laws of which have just been stated, is called the regular or *specular* reflection, which is from a Latin word signifying mirror; but the quantity thus reflected is less than the incident light. The light incident on an opaque body is separated, in fact, into three parts; one is reflected regularly, another *irregularly*—that is, in all directions—while a third is absorbed by the reflecting body.

Thus, if, in the experiment represented in fig. 319, the beam Bm be caught on an unpolished surface, instead of on a mirror, not only will it be seen in the direction mC, corresponding to regular reflection, but it will be seen in all positions, whence it is concluded that light is reflected in all directions and under all obliquities, which is apparently contrary to the laws of reflection. Such reflection is illustrated in fig. 320.

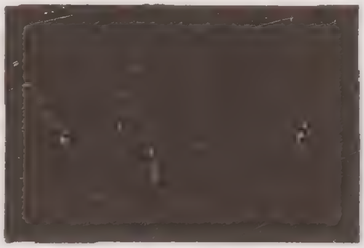


Fig. 320.

This irregularly reflected light is called *scattered* or *diffused light*; it is that which makes bodies visible; it has its origin in the structure of bodies themselves, which are never perfectly smooth, and, from their slight roughnesses, present an infinity of small facets variously inclined, which reflect light in all directions.

Diffused light plays an important part in the phenomena of vision. For while luminous bodies are visible of themselves, opaque bodies are only so in consequence of the diffused light which they send in all directions. Thus, when we look at a piece of furniture, a table, or a flower, it is the diffused light reflected on all sides and in all directions by the object which enables us to see it, in whatever direction we may be placed in reference to the light which illuminates it. When bodies only reflect light regularly, it is not them we see, for, acting like mirrors (336), they only give us the image of the luminous body whose light they send towards us. If, for example, a beam of the sun's light, passing through

a hole in the shutter, falls on a well-polished mirror in a dark room, the more perfectly the light is reflected, the less visible is the mirror in the different parts of the room. The eye does not perceive the image of the mirror, but that of the sun. If the reflecting power of the mirror be diminished by sprinkling on it a light powder, the sun's image becomes feebler, but the mirror is visible from all parts of the room. Smooth, polished, perfectly reflecting surfaces, *if such there were*, would be invisible, and absolutely non-reflecting surfaces would also appear all equally black, and the two would be confounded with each other. The pencil of light seen by admitting light into a dark room is visible in consequence of the little motes floating in the air. If the sides of a glass vessel be coated with the transparent liquid glycerine, and the electric light be allowed to fall on it, its path is at once visible; but after the lapse of some time the floating particles settle down and are fixed by the glycerine, and, as Tyndall has shown, the electric light now traverses the space without being seen. This may be illustrated by the following simple experiment. A beam of light admitted through a hole in the shutter of a dark room is directed upon a mirror, from which it is reflected into a large wide-mouthed glass jar. If some smoke has been produced in the jar by dropping a piece of lighted touch-paper in it, the whole space inside is luminous, which is not the case when the jar contains ordinary air. Two bodies, one white and the other black, placed in darkness, are quite invisible, for that which is white, not receiving any light, can reflect none.

In the case of scattered reflection, the actual amount of light reflected to the eye by a surface of any kind is only a fraction of the light which falls upon it, and depends on the nature of the surface. If we call the incident light 100, we have for that reflected from freshly fallen snow 78, white paper 70, white sandstone 24, porphyry 11, and ordinary earth 8.

It is the diffused light reflected by the solid particles floating in the air, by the clouds, by the ground, which illuminates our rooms and all bodies not directly exposed to the sun's rays; and the larger the quantity of diffused light which a body sends towards us, the more distinctly can we distinguish it. From the inside of our rooms we well see external objects, for they are powerfully illuminated; but from the outside we only see confusedly the objects in the interior of apartments, for they receive but little light. If the atmosphere were perfectly transparent, there would

be complete darkness immediately after the sun had set; but before sunrise, as well as after sunset, there is a considerable amount of light spread over the earth's surface. This is due to the fact that the upper layers of the air diffuse the light which they receive before sunrise and after sunset, and thus give rise to the phenomenon known as *twilight*. In the ordinary sense of the word, this is as long as we can still read in the open, which is the case when the sun is 6° below the horizon. What is called *astronomical twilight* is when the smallest stars visible to the naked eye just disappear; this is when the sun is 18° below the horizon. In the shortest summer nights twilight does not cease in our latitudes, because the sun at midnight is not 18° below the horizon. The more transparent and the purer the air, the shorter is twilight, while it is prolonged by light clouds in the higher regions. On lofty mountain summits, where a considerable part of the atmosphere is below the level, the direct rays of the sun are painfully intense, and the sky is by contrast dark.

335. **Direction in which we see bodies.**—Whenever a pencil of light passes in a straight line from a body to our eye, we see

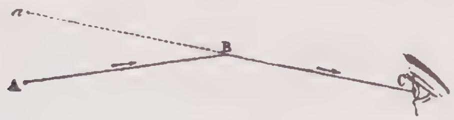


Fig. 321.

it, so far as direction is concerned, exactly as it is; but if, in consequence of reflection, or any other cause, the pencil of light is deviated in its route, if it ceases to come to us in a straight line, we no longer see the body in its proper place, but *in the direction of the pencil of rays at the moment it enters the eye*. Thus, if the pencil AB is deflected at B (fig. 321), and takes the direction BC, the eye does not see the point A at A, but at *a*, in the prolongation of CB.

This principle is general, and on it are based the numerous effects of vision which mirrors and lenses present.

336. **Mirrors. Images.**—*Mirrors* are bodies with polished surfaces, which show by reflection objects presented to them. The place at which objects appear is their *image*. According to their shape, they are divided into *plane* and *curved* mirrors.

We have an example of a plane mirror in the looking-glasses which adorn our apartments. In these mirrors it is not the glass which reflects light in sufficient quantity to give neat and well-defined images ; it is a layer of metal on the back of the glass. This layer is an *amalgam* of tin ; that is, an alloy of this metal with mercury. The glass has only the effect of giving the metal the necessary polish, and of preserving it from external agencies which tend to tarnish it.

Metal mirrors are also constructed of gold, silver, steel, tin. They all have the defect of tarnishing on contact with the air. The first mirror was doubtless the surface of clear water. The mirror of liquid mercury is often used by astronomers in observing the altitudes of heavenly bodies.

337. **Formation of images in plane mirrors.**—*Plane mirrors* are those whose surface is plane. To understand the formation of images in these mirrors, let us first consider the case in which a small object is placed in front of such a mirror — for instance, the flame of a candle. A pencil of light emitted by a point in this flame, and falling on the mirror, is reflected there, as shown in fig. 322. But it follows, from the laws of reflection, that each ray of this pencil retains, in reference to the mirror, the same obliquity as it had before ; whence it follows that the reflected rays have the same divergence in reference to each other as the incident rays. Hence, if we imagine the reflected pencil

Fig. 322.

prolonged behind the mirror, all the rays composing it will coincide in the same point. But as we always see objects in the direction which the rays of light have when they reach us (335), it follows that the eye, which receives the reflected pencil, should see the particular luminous point in the flame of the candle just in the place where the prolongations of these reflected rays coincide. There, in fact, is produced the image of this point as seen in fig. 322.

If now, instead of considering a single luminous point placed in front of the mirror, we consider a body of any dimensions, we

Fig. 323.

need do no more than apply to each of its parts what has been said in reference to a single luminous point, in order to understand the formation of its image. For instance, in fig. 323, which represents a person in front of a mirror, the rays from the forehead are reflected from the mirror, and return to the eye, producing an image of the forehead. In like manner the rays from the chin, being reflected from the mirror, reach the eye as if they proceeded from the chin of the image, and so on with all parts of the face; hence the illusion which makes us see our image on the other side of the mirror.

338. **Nature of the images in plane mirrors. Real and virtual**

images.—If, when looking in a mirror, we raise the right hand, it is the left which seems raised in the mirror; and if we raise the left hand, the right seems raised. We should falsely express this transposition of the parts of the image in reference to the object if we merely said that the image was reversed; if it were nothing else than the object reversed, in raising the right hand the image should also raise the right hand, while it really is the left which is raised.

This special relation which exists between an object and its image is expressed by saying that the image is *symmetrical* in reference to the object; that is, that any point of the image is arranged behind the mirror in identically the same manner as the corresponding point of the object in front. For it may be shown by geometrical considerations that these two points are equidistant from the mirror, and on the same right line, which is at right angles to the surface. From the respective distance and position of the different parts of the object and of its image, it is concluded that the latter is of the same magnitude as the object, and equidistant from the mirror.

Lastly, images formed in plane mirrors are *virtual*; by which we mean that they have no real existence, and are only an illusion of the eyes. For in fig. 322, as well as in fig. 323, the light, as it does not pass behind the mirror, cannot form any image there, and that which we see has no existence; this is expressed by the word *virtual* as opposed to *actual* or *real*. Virtual images are only an optical illusion; but we shall soon see that, in concave mirrors and in lenses, *real* images are produced which can be received on screens, and can produce certain chemical actions; this is a criterion by which they are distinguished from virtual images.

339. **Multiple images formed by glass mirrors.**—Metal mirrors which have but one reflecting surface only give one image: this is not the case with glass mirrors, the two surfaces of which reflect, though to unequal extents. For if we apply any object—the point of a pencil, for instance—against a thick piece of polished glass, at first when it is looked at obliquely a very feeble image is seen in contact with it; then, beyond it, another and far brighter one. The first image is due to the light reflected from the front surface of the plate—that is, from the glass itself; while the second is due to the light which, penetrating into the glass, is reflected from the layer of metal by which the hinder face is covered. The difference in brightness of the two images is readily explained;

glass being very transparent, only a small quantity of light is reflected from the first face of the mirror, which gives the less intense image; while the greater part of the incident light passing into the mass is reflected from the surface of the metal, and gives the brighter image. Fig. 324 shows the multiple images of a candle obtained by reflection with a glass plate, the two surfaces of which each act as reflectors.

Fig. 324.

The double reflection from ordinary plate-glass mirrors is prejudicial to the sharpness of images, so that, in scientific observations, mirrors of metal are usually preferred to glass ones.

340. **Reflection from transparent bodies.** — We have seen that glass, notwithstanding its transparency, reflects a sufficient amount of light to give images which, though feeble, are distinct. The same is the case with water and other transparent liquids. Thus, on the borders of a pool we see formed in the water the reversed image of objects on the opposite bank. We say *reversed* image, so as to express the appearance; but more strictly we should say symmetrical, from what has been before said (338). A highly varnished picture is a mirror, and, if placed so as to reflect the light, the varnish prevents spectators from seeing the subject of the picture.

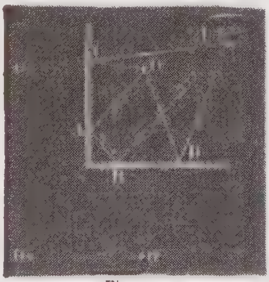


Fig. 325.

341. **Multiple images from two plane mirrors.**—When an object is placed between two plane mirrors, which form an angle with each other, either right or acute, images of the object are formed, the number of which increases and the

brightness of which decreases as the angle between the mirrors decreases. If they are at right angles to each other, three images are seen, arranged as represented in fig. 325. The rays OC and OD, from the point O, give, after a single reflection, the one an image O′, and the other an image O″, while the ray OA, which undergoes two reflections, at A and B, gives the third image, O‴. When the angle of the mirrors is 60°, five images are produced, and seven if it is 45°. The number of images continues to increase in proportion as the angle diminishes, and when it is zero—that is, when the mirrors are parallel—the number of images is theoretically infinite. In general, if two mirrors are inclined to each other they produce twice as many images, counting the object itself as one, as the angle between them is contained in 180°.

342. **Multiple images in two plane parallel mirrors.**—In this case the number of images of an object placed between them is theoretically infinite. Physically the number is limited, for as the incident light is never totally reflected, some of it being always absorbed, the images gradually become fainter, and become ultimately invisible.

Fig. 326 shows how the pencil reflected once from M gives at I the image of the object L at a distance $mI = mL$; then the pencil L*b*, reflected once from the mirror M and once from N, furnishes the image I′ at a distance $nI' = nI$; in like manner the pencil L*c*, after two reflections on M and one on N, forms the image I″ at a distance $mI'' = mI'$, and so on for an indefinite series. The images *i*, *i′*, *i″*, are formed in the same manner by rays of light which, emitted by the object L, fall first on the mirror N.

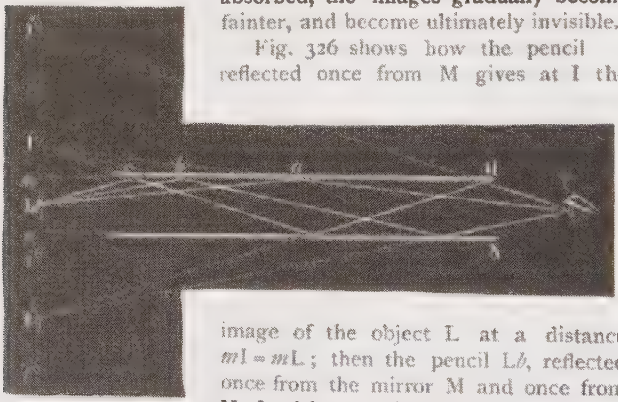


Fig. 326.

The *Kaleidoscope*, invented by Sir D. Brewster, depends on this property of inclined mirrors. It consists of a tube, in

which are three mirrors inclined at 60°; one end of the tube is closed by a piece of ground glass, and the other by a cap provided with an aperture. Small irregular pieces of coloured glass are placed at one end between the ground glass and another glass disc, and on looking through the aperture, the other end being held towards the light, the objects and their images are seen arranged in beautiful symmetrical forms; by turning the tube, an almost endless variety of these shapes is obtained.

343. **Concave mirrors.**—There are many kinds of curved mirrors. Those most in use are called *spherical mirrors*, from their curvature being that of a sphere. They may be either of metal or of glass, and are either *concave* or *convex*, according as the reflection is from the internal or the external face of the mirror. For experiments on a small scale the phenomena of concave mirrors may be shown by means of a curved watch-glass which is blackened on the convex side; in like manner the phenomena of convex mirrors may be shown by one which is blackened on the concave side.

To facilitate the study of concave mirrors we will first consider what is called a *section*—that is, the figure obtained by cutting it into two equal parts. Let M N (fig. 327) be the section of a spherical mirror, and C the centre of the corresponding sphere. In reference to the sphere this point is called the *centre of curvature*; the point A is the *centre of the mirror*. The right line ACX, which passes through A and C, is the *principal axis* of the mirror; any right line, *i*C*a*, which simply passes through the centre C, and not through the centre of figure, A, is a *secondary* axis. The angle MCN, formed by joining the centre and extremities of the mirror, is the *aperture*. A *principal* or *meridional section* is any section made by a plane through its principal axis. In speaking of mirrors those lines alone will be considered which lie in the same principal section. There is only one principal axis, but the number of secondary axes is unlimited.

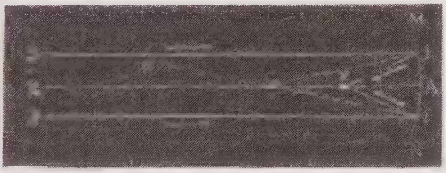


Fig. 327.

The manner in which light is reflected from curved mirrors is

easily deduced from the laws of reflection from plane mirrors, by considering the surface of the former as made up of an infinitude of extremely small plane surfaces, all equally inclined to each other so as to form a regular spherical surface. Accordingly, on this hypothesis, when a ray of light falls upon any point whatever of a curved mirror, it is really from a small plane mirror that it is reflected; the reflection takes place then in accordance with the laws already laid down (336).

344. **Principal focus of a concave mirror.**—The small facets, of which we have assumed concave mirrors to be made up, being all

Fig. 328.

inclined towards a common centre, which is the centre of curvature of the mirror, it follows from this obliquity that the rays reflected by these mirrors tend to unite in a single point, which is called the *focus*, as we have already seen in the case of heat (228).

To explain this property of curved mirrors, let SI be a ray falling upon such a mirror parallel to the axis AX (fig. 327). From the hypothesis assumed above, the reflection takes place at I, on an infinitely small plane mirror. It can be shown geometrically that the perpendicular to this small mirror is represented by

the right line CI from the centre C to the point I. Hence the angle SIC represents the angle of incidence, and if we imagine, on the other side of the perpendicular, a straight line IF, which makes with CI an angle FIC, equal to CIS, this straight line will be in the direction of the reflected ray.

But when the incident rays are parallel to the axis of the mirror, as in the above example, it may also be proved geometrically, if I is not far from A, that the point F, where the luminous rays cut the axis, is the middle of AC ; that is, it is equidistant from the centre of curvature and the mirror. This property being common to all rays parallel to the axis, it follows that, after reflection, these rays will all coincide in the same focus, F, as shown in the figure.

The focus described above—namely, the point halfway between the centre of curvature and the mirror—is called the *principal focus* ; it is the point of convergence of rays which before reflection were parallel to the principal axis. An example of this is seen in fig. 328, which represents a pencil of sunlight falling upon a concave mirror. If a small ground-glass screen be placed where the reflected rays tend to concentrate themselves, a very luminous point, or rather small circle, which is the image of the sun, will appear at the principal focus.

345. **Conjugate foci.**—In the foregoing examples we have considered the case of pencils of parallel rays, which presupposes that the luminous object is at an infinite, or at all events a very great, distance. Let us now consider the case in which, the source of light being at a small distance, the rays falling on the mirror are divergent, as shown in fig. 329. Here the reflected rays are converged, but less so than in figs. 327 and 328, which results from the divergence of the light in arriving on the mirror. Hence the point where the reflected rays coincide is more distant from the mirror than the principal focus ; instead of being at F, the principal focus, it is at *b*, between the points F and C. This point, *b*, where the rays coincide, is also a focus. To distinguish it from the principal focus, F, it is called the *conjugate focus* of the point B, from a Latin word meaning *connected* ; for there is this connection between the position of the luminous point B and that of its focus, that when the luminous object is at B, the rays form their focus at *b* ; and that, conversely, if the luminous object is removed to *b*, the reflected rays form their focus at B. Thus B and *b* are conjugate to each other.

There is only one principal focus, but the position of the conjugate focus of B varies as B varies. For, suppose that in fig. 329 the candle is removed away from the mirror, as the incident rays make then gradually increasing angles of incidence with the radius drawn to the point of incidence, the angles of reflection increase too, and the focus *b* approaches the point F, with which it will ultimately coincide, when the candle is so far distant that the incident rays are virtually parallel.

If, on the contrary, the candle is brought nearer the mirror, the rays falling upon it make angles with the radius at the point of incidence, which are gradually smaller ; the angles of reflection decrease also. Hence the rays reflected by the mirror coincide at gradually greater distances, and *b* advances towards the centre C ; if the candle comes nearer the point, so as to coincide with it, the

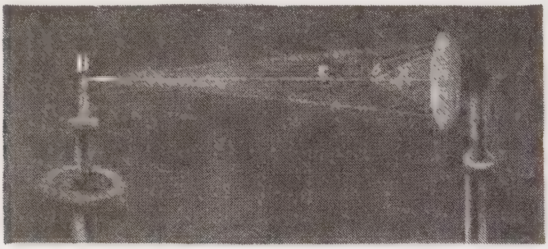


Fig. 329.

same will be the case with the image *b* ; so that the candle and its image will coincide at C.

Lastly, if the candle, always approaching the mirror, passes between the centre of curvature and the principal focus F, the conjugate focus *b*, continually removing from the mirror, passes on the other side of the centre, and is formed at a greater distance the nearer the luminous body is to the principal focus ; if the candle coincides with this latter point, the conjugate focus forms at an infinite distance—that is, the reflected rays become parallel.

These different effects of reflection are a consequence of the constant equality between the angle of incidence and the angle of reflection. They may be very simply verified by placing in a dark room a candle in front of a concave mirror successively in various

positions, and then ascertaining by trial where the luminous focus is formed on a small screen of paper held in the hand, and brought nearer to or farther away from the mirror.

346. **Virtual focus.**—After having described the different positions of the point in which the rays reflected by a concave mirror coincide, when the luminous body is either beyond or in the principal focus, we have to inquire what becomes of these same rays when the source of light is at any point P, which is nearer the mirror than the principal focus (fig. 330).

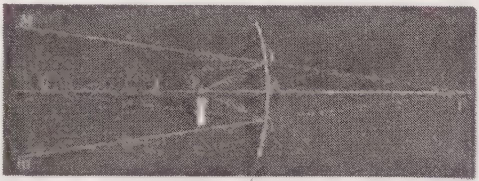


Fig. 330.

In this case the reflected rays form a diverging pencil, and cannot therefore produce any focus in front of the mirror; but as regards the eye which receives them, they produce exactly the same effect as in plane mirrors (336); that is, the eye receives the same impression from the reflected rays IM and *im* as if the candle were placed behind the mirror at the point *p*, where the prolongations of these rays coincide. Hence the image of the candle is seen at *p*, but as the light does not penetrate behind the mirror, this image does not really exist: hence the focus which seems to form at *p* is called the *virtual* focus, the expression being understood in the same sense as in plane mirrors.

347. **Formation of images in concave mirrors.**—Concave mirrors give rise to two kinds of images, real and virtual. Their formation is readily understood after what has been said respecting conjugate and virtual foci. We may, however, remark that when a luminous or illuminated point is situated on the principal axis of a mirror, its focus, real or virtual, is always formed on this axis. This is the case in figs. 329 and 330; but if the luminous point is on a secondary axis, the focus is formed on this axis. Thus if in fig. 327 a candle were placed at *d*, on the secondary axis *i*C*d*, the reflected rays would form their focus on the line C*i*. That being admitted, let us see how images are formed in concave mirrors.

Real image.—If a person places himself at a certain distance in

front of a concave mirror, he no longer sees himself erect and of the ordinary size, as in plane mirrors, but reversed and much smaller. To this image the name *real image* is given to express that it is not an illusion, like that seen in plane mirrors, but that it has a real existence, for it may be received on a screen. If the mirror is placed in front of a brightly lighted object, as, for instance, before a building on which the sun is shining, and a person places himself a little on one side, holding a small white screen in the position in which the conjugate focus should be formed, the pencils

Fig. 331.

from the various parts of the edifice are reflected from the mirror and fall on the screen, forming in miniature an image not less remarkable for the colour than for the fidelity of the outlines (fig. 331); it has no other defect than that of being reversed.

The formation of this image is readily explained. For from what has been said in reference to conjugate foci (345), each point of the image is the conjugate focus of the corresponding point of the illuminated body, and is on the same secondary axis. But as all the secondary axes from the various points of this body cross in the

centre of curvature of the mirror, it follows, as shown in the figure, that the rays from the higher parts of the body converge towards the lower part of the image, and that conversely rays from the foot unite on the higher parts of the same image, which explains how it is that the latter is reversed.

It is to be observed that the real image in concave mirrors is not always smaller than the object illuminated, as is the case in the above two figures ; it may also be larger. This is the case when, the object being placed between the principal focus and the centre of curvature, its image is formed outside the latter, and it is then larger the greater the distance at which it is formed.

Fig. 332.

Virtual image.—When a person is placed at a certain distance in front of a concave mirror, he sees himself smaller and reversed. If he comes nearer, there is a point at which no image is seen. This is the case when he is between the centre and the principal focus, for the image is then formed behind him. If he is in the principal focus itself, there is no image. For we know (344) that the rays of light proceeding from this focus, after being reflected from a concave mirror, produce a parallel pencil ; hence as the rays coincide neither behind nor in front of the mirror, they cannot give rise to any image. But, approaching the mirror, the image suddenly reappears, and, instead of being smaller and reversed as it was, is now erect and much enlarged, as in fig. 332. This is the *virtual image.*

To account for the formation of this image, we must recall what has been said about virtual foci (346) : first, that they are only formed as long as the luminous or illuminated object is between the principal focus and the mirror ; second, that the virtual focus, or, what is the same thing, the virtual image of any point of the object, is behind the mirror on the secondary axis which passes through this point. Hence, the head of the observer being placed between the mirror and the principal focus (fig. 333), all rays from any point, *a*, of the face return to the eye after

reflection, as if they proceeded from the point where the prolongations of the reflected rays coincide on the secondary axis, C*a*A. In like manner, rays from the point *b* return to the eye, as if they were emitted from the point B, which is on the prolongation of the secondary axis, C*b*B. The eye sees, therefore, at AB, an erect and enlarged image.

348. **Formation of images in convex mirrors.**—We have already seen that convex mirrors are spherical mirrors, which reflect light from their external surface—that is, on the bulbed side. Whatever the distance of a luminous or illuminated object placed

Fig. 333.

in front of these mirrors, we never obtain any other than a virtual image situated on the other side of the mirror, always erect and smaller than the object. This may be verified by looking in a mirror of this kind as represented in fig. 334. The formation of this image can be easily explained by an inspection of fig. 335. It is here smaller than the object, for it is nearer than the latter to the point where the secondary axes coincide, while the reverse is the case with the formation of the virtual image in the concave mirrors.

The images of objects seen in concave or convex mirrors appear smaller or larger, but otherwise similar geometrically, except

in the case where some parts of a body are nearer the mirror than others. The distortion of features observed on looking into a spherical garden mirror is more marked the nearer we are to the glass. Objects seen in *cylindrical* or *conical* mirrors appear ludicrously distorted. From the laws of reflection the shape of such a distorted figure can be geometrically constructed. In like manner distorted images of objects can be constructed which, when viewed in such mirrors, appear in their true proportions. They are called *anamorphoses.*

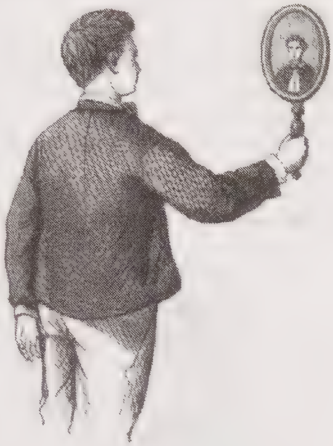


Fig. 334.

349. **Applications of mirrors.** The applications of plane mirrors in domestic economy are well known. Mirrors are also frequently used in physical apparatus for sending light in a certain direction. The sun's light can only be sent in a constant direction by making the mirror movable. It must have a motion which compensates for the continual change in the direction of the rays produced by the apparent daily motion of the sun. This result is obtained by means of a clockwork motion, to which the mirror is fixed, and which causes it to follow the course of the sun. Such an apparatus is called a *heliostat.* The reflection of light is also used to measure the angles of crystals by means of the instruments known as *reflecting goniometers.*

Concave mirrors have been employed for burning mirrors, and are used in telescopes (392), as they only give one image. They also serve as reflectors, for conveying light to great distances, by placing a luminous object in their principal focus, as in search lights. For this purpose parabolic mirrors are preferable.

The reflection of light from mirrors was applied by Mance in signalling at great distances by means of the sun's light with an instrument called the *heliograph.*

This apparatus consists essentially of a mirror about 4 inches in diameter mounted on a tripod, and provided with suitable adjust-

ments, so that the sun's light can be received upon it and reflected to a distant station. An observer then can see through a telescope the reflection of the sun's rays as a spot of light. The mirror has an adjustment by which it can be made to follow the sun in its apparent motion. There is also a lever key by which the signaller can deflect the mirror through a very small angle either to the right or left, and thus the observer at a distant station sees corresponding flashes to the right or left. Under the subject of Telegraphy it will be seen how these alternate motions can be used to form an alphabet.

The heliograph proved of essential service in the campaigns in Afghanistan, and quite recently in South Africa. Instead of any

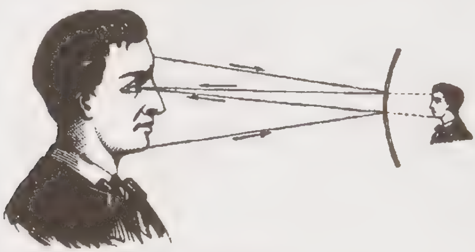


Fig. 335.

special form of apparatus, an ordinary shaving mirror or hand glass is frequently used; and the proper inclination having been given so as to send the sun's rays to the distant station, which is very easily effected, the signals are produced by obscuring the mirror by sliding a piece of paper over it for varying lengths of time. In this way longer or shorter flashes of light are produced, which, properly combined, form the alphabet.

Of course this mode of signalling can only be used where the sun's light is available, but it has the advantage of being simple and portable. Signals have been sent in very fine weather at the rate of 12 words a minute, through distances of 40 miles.

CHAPTER III

REFRACTION OF LIGHT

350. **Phenomenon of refraction.**—When a pencil of light passes more or less obliquely from one transparent medium into another—for instance, from air into water, or from air into glass—it undergoes a deflection from the straight line in which it proceeds, as seen in fig. 336, which represents a ray of light passing from air into water. This change in direction is called *refraction*, from a Latin word meaning *broken*; for the ray is, in fact, broken at the point A, where it passes from the direction LA to the direction AK.

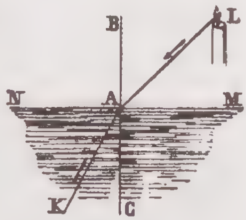


Fig. 336.

The ray LA is called again the *incident ray*; AK is the *refracted ray*; the perpendicular, BC, drawn at the point of incidence, A, of the surface, MN, which separates the two media, is called the *normal* or *perpendicular*; the angle, BAL, is called the *angle of inciaence*; and the angle, CAK, the *angle of refraction*. If the angle of incidence is zero—that is, if the incident ray is perpendicular to the surface—the same is the case with the refracted ray, and light thus travels in a straight line; that is, it is not refracted.

Thus, if a pencil of the sun's rays which enters through a shutter in a dark room be allowed to fall on a glass vessel containing water (fig. 338), the pencil can be very distinctly seen to be broken as it passes from air into water, especially if some light powder has been diffused through the air and the water so as to make the pencil more visible (334).

351. **Laws of refraction.**—When a ray of light is refracted in passing from one medium to another of a different refractive power, the following laws prevail :—

I. *Whatever the obliquity of the incident ray, the ratio which the sine of the incident angle bears to the sine of the angle of refraction is constant for the same two media, but varies with different media.*

II. *The incident and the refracted rays are in the same plane, which is perpendicular to the surface separating the two media.*

These laws may be understood by reference to fig. 337, in which the ray, LA, passes from air into water. If, from the point of incidence, with a radius equal to unity, a circle be described, and from the points *m* and *p*, where it cuts the incident and refracted rays, perpendiculars, *mn* and *pq*, are drawn to the normal, BC, the former is called the *sine of the angle of*

Fig. 337.

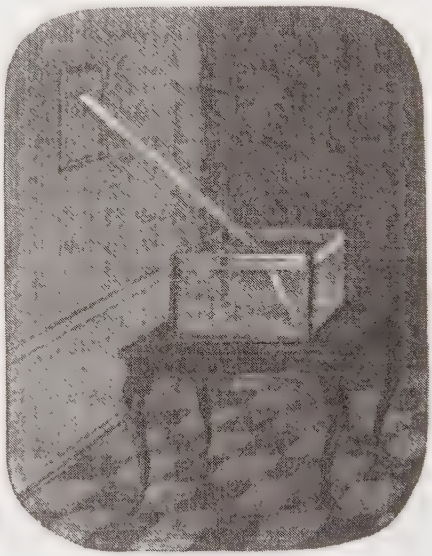


Fig. 338.

incidence, and the second the *sine of the angle of refraction.*

It is the ratio of these sines, these perpendiculars, which is constant ; that is, *pq*, for instance, being three-quarters of *mn*, if the angle of incidence diminishes or increases, the angle of refraction does so too, but the sine of the angle of incidence will always be four-thirds of the sine of the angle of refraction.

This constant ratio is called the *refractive index*, or *index of refraction of water*; its value varies with different transparent media. Thus from air to water the ratio is $\frac{4}{3}$, from air to glass $\frac{3}{2}$,

and from air to diamond it is $\frac{5}{2}$; or, 1·33, 1·5, and 2·5 are the refractive indices respectively of water, glass, and diamond with respect to air.

The above laws may be demonstrated by means of the apparatus represented in fig. 339, which resembles that by which the laws of reflection were shown (fig. 319), except that, instead of the mirror *m*, there is a semi-cylindrical glass vessel R filled with liquid, and that the surface is at the same level as *m*. The pencil of light from the source S is reflected from the mirror M, and passing through the tube *c*, it falls on the surface of the water at O. Here it is refracted on entering the water, and the path of the ray may be followed by turning the limb K until a bright spot appears on the screen *e*. The angle KOE which the limb K makes with the perpendicular IE to the surface at the point of incidence, is the angle of refraction. Now the angle EOF is equal to the angle MOI, which is the angle of incidence, and the line F H is accordingly the sine of this angle, and can be read off on the scale below to which it is parallel, and the sine of the angle KOE is given directly on the scale.

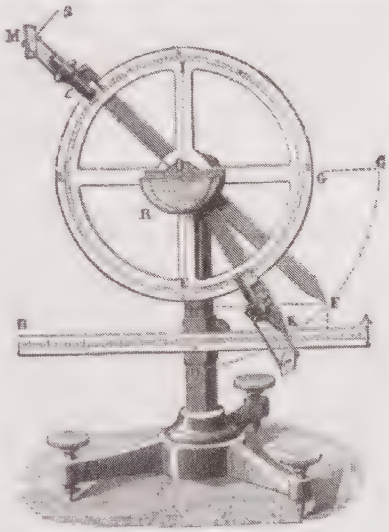


Fig. 339.

Now, by displacing the position of the mirror, M, so as to get different angles of incidence, we get also different angles of refraction, but the ratio of their sines is always constant; that is, if the sine of the angle of incidence becomes twice or thrice as large, the sine of the angle of refraction increases in the same ratio, which demonstrates the first law. The second law follows from the arrangement of the apparatus, for the plane of the graduated limb is perpendicular to the surface of the liquid in the semi-cylindrical vessel.

352. **Refracting substances.**—When a ray of light is refracted in passing from one medium into another, sometimes it approaches the perpendicular, forming an angle of refraction which is less than the angle of incidence, as is the case in the above figure; sometimes, on the contrary, it is deflected away, forming an angle of refraction which is greater than the angle of incidence. In the first case the second medium is said to be more *refractive* than the first, and in the second case it is less so.

Different substances differ greatly in respect of their refractive power. Diamond is the most refractive of all bodies. Gases are less refractive than water; their refracting power is increased by condensing them—that is, by increasing their density.

353. **Experimental illustration of refraction.**—The deviation undergone by luminous rays, on passing from one medium to another, may be demonstrated by numerous experiments.

Thus, let a coin be placed at the bottom of an opaque vessel (fig. 340), and let the eye be placed so that the edge of the vessel just intercepts the view of the coin. If, now, without altering the position of the observer, water be gradually poured into the vessel, at first only the edges of the coin will be seen, then half, and finally the entire piece. Now, what has taken place here? Nothing has been changed in the position of the eye, or in that of the coin; it is the rays from the latter which have changed their direction. Those which were before intercepted by the sides of the vessel are so still; but rays which, before there was water in the vessel, passed above the observer's head, are directed towards the eye, being refracted in passing from water into air, so as to diverge from the perpendicular to the surface of the liquid, as represented in the figure.

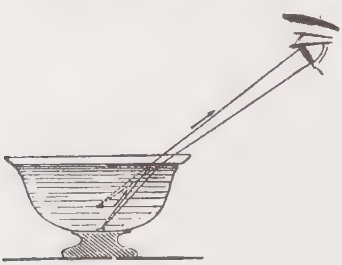


Fig. 340.

354. **Various effects of refraction.**—Refraction of light produces various phenomena, the effect of which is to deceive the eye by making us see objects in other than their true positions; thus, we do not see fish in the place they actually occupy, but a little higher. It will be understood that in virtue of the same principle

we see the bottom of a clear river or a pond higher than it really is ; water that appears to be 3 feet deep is in reality 4 feet.

The same cause makes a stick half immersed in water appear broken when it is looked at at the side ; for the portion out of the water is seen in its true position, while that which is immersed appears raised, from which results the appearance of the stick being broken at the surface of the liquid (fig. 341). The part of a ship or boat visible under water appears much flatter than it really is.

Fig. 341.

In conclusion, the influence may be mentioned which refraction exerts upon the apparent rising and setting of the stars, which we can see a little before they are above the horizon and a little after they have sunk below it. To explain this phenomenon, let us suppose the atmosphere divided into layers parallel to the surface of the globe, as represented in fig. 342. Owing to the pressure exerted by the upper layers upon the lower ones, the latter are more dense (140), and therefore more refractive; for, as we have seen, the refracting power of the air increases with its density (352). The sun's rays, which penetrate the atmosphere, are always reflected in the same direction as they pass from one layer to another ; hence their path, instead of being that of a straight line, will be really somewhat curved. Thus it is that, while the sun is at S, below the horizon, an observer at A, on the surface of the earth, will see it raised by an amount which is generally equal to its apparent diameter. The air renders the sun visible when it is in fact below the horizon, in just the same way as a coin in fig. 340

Fig. 342.

is made visible. Hence in astronomical observations a correction must be made for this source of error, in order to obtain the true position of a star. This principle explains why the coast of France is often seen from Hastings, though a straight line connecting them would, owing to curvature, pass through the sea.

355. **Change of refraction to reflection.**—Whenever light passes from one medium into a more refractive one, from air into water, for instance, there is nothing to prevent the refracted ray from approaching the perpendicular to form an angle smaller than the angle of incidence; but if, on the contrary, the second medium is less refractive than the first, in which case the refracted rays recede from the perpendicular, there is a limit to their deviation, and hence refraction may become impossible.

To get a clearer idea of this, let us imagine a hollow glass sphere half filled with water (fig. 343), and a ray of light, LA, to enter the liquid without being refracted, which is the case when it penetrates at right angles the small facet which we can always conceive to exist at the point at which it enters. This ray is refracted at A in passing from water into air, and diverges from the perpendicular, BAC, in the direction AR. Now, conceive the luminous body to move gradually from AC; as the angle of incidence, CAL, increases, the angle of refraction, BAR, does so too; and the angle of incidence may acquire such a magnitude that the refracted ray emerges parallel to the surface, AM, of the liquid. This angle of incidence is what corresponds to the *limit of refraction*. It is called the *critical angle*. For, for any greater angle of incidence, the angle of refraction should exceed the angle BAM; and the light would then take below AM a direction such as A*r*. There would, however, then be no refraction, for the light, always travelling through water, does not change its medium. If the incident ray be then represented by *l*A, and if we measure the two angles *l*AC and CA*r*, it will be found that they are exactly equal, which shows that at the point A the light is reflected according to the laws of reflection.

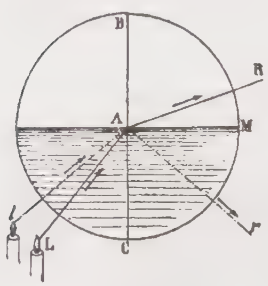


Fig. 343.

This kind of reflection at the surface which separates two

media of different refracting power is called ***internal reflection*** ; it is also called *total reflection*, for here the whole of the incident light is reflected, which is never the case in ordinary reflection, even in the best polished surfaces (333).

The phenomenon is frequently met with ; thus, if a silver spoon be placed in a glass of water, and the glass be raised above the eye, the surface of the liquid is seen to be brighter than the polished metal, and one portion of the spoon forms an image in it as in a mirror. Similar effects are met with in aquariums. The upper surface of the liquid, when looked at from a suitable position below, gives a reflected image of the objects it contains. If a stout test tube (fig. 344) half full of water is placed in a vessel of water, standing on a sheet of white paper, $p'p$, so that it makes an angle of about 60°—but at any rate over 48°—on looking at the tube from above, the rays $a'a$ reflected from the portion of the tube which contains air are far more brilliant than the rays $b'b$ reflected from that in which is the water. If a layer of benzole be poured on water contained

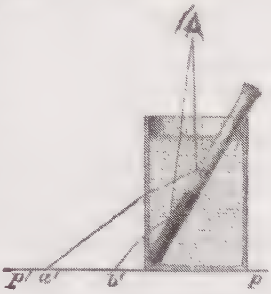


Fig. 344.

Fig. 345.

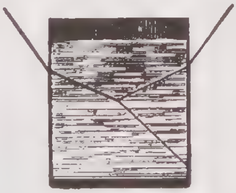


Fig. 346.

in a small beaker (fig. 345), and the bounding surface of the two liquids be looked at obliquely from above, it appears with the brightness of silver, for at a certain angle the rays cannot pass into the water, but are totally reflected.

In the second vessel are water and bisulphide of carbon (fig. 346). Here the bounding surface appears dull ; only a portion of the rays are reflected there, most of them passing from the water into the denser and more highly refractive bisulphide of carbon.

Bubbles in water, again, glisten like pearls, and cracks in

transparent bodies like strips of silver, for the oblique rays are totally reflected. The lustre of transparent bodies bounded by plane surfaces, such as the lustre of chandeliers, arises mainly from total reflection. This lustre is more frequent and more brilliant, the smaller the limiting angle ; the lustre of diamonds, for this reason, is the most brilliant. In cutting precious stones they are so shaped that the rays do not emerge in consequence of ordinary refraction, but, being totally reflected, have unusual lustre.

Masses of small particles of perfectly transparent bodies separated by particles of air are themselves opaque. Thus, white sand is powdered transparent quartz ; foam is made up of transparent thin layers ; cloud, fog, snow, are accumulations of particles of transparent water or ice. In all such cases the incident light which penetrates must pass innumerable times into the air, which has a different refractive index, by which it is gradually totally absorbed. If the interstices between the particles of powdered glass are filled up with rock oil, the refractive index of which is nearly that of glass, the glass appears again transparent. If a false diamond be placed in a transparent liquid which has the refractive index of true diamond, it can at once be detected by its being visible.

This may be illustrated by means of the apparatus represented in fig. 347, which consists of a tube containing bisulphide of carbon, while through the cork passes a flint-glass rod, these substances having almost exactly the same

Fig. 347.

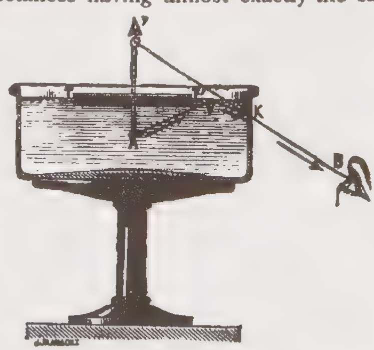


Fig. 348.

refractive index. When the tube is inverted so that the rod is completely immersed, this latter becomes invisible or nearly so.

A cork disc, TT′, about an inch and a half in diameter (fig. 348), to which is fixed perpendicularly a brass pin, A, about an inch long, is floated on water. With these dimensions the rays from the pin which strike the surface of the water outside the cork do so under an angle *greater than the limiting angle*, and are therefore totally reflected; so that to an eye placed in any position above the surface of the water the pin is invisible, while if the eye is placed below the surface, as at B, an image of the pin is seen by reflection.

The apparatus represented in fig. 349 affords a beautiful illustration of the effects of internal reflection. It consists of a metal cylinder filled with water, which is made very slightly turbid by adding a few drops of solution of mastic, or fluorescent by the addition of eosin, having near an aperture the bottom which can be closed by a stopper. Exactly opposite is a sort of glass window in the side, near which is a plano-convex lens (360); the focal length of this is such that the luminous cone from a lime or electric light just falls on the aperture. When the stopper is removed the water jets out and, as may be shown, in the form of the curve known as the *parabola*. Now, from the property of this curve, any ray of light which strikes against the inside does so under an angle greater than 48°, which is the critical angle; accordingly, this light undergoes a series of successive internal reflections. The fluorescence or the turbidity, by scattering a portion of the light, enables it to emerge, which it could not do if the water were perfectly clear, and the jet appears like a stream of white-hot metal.

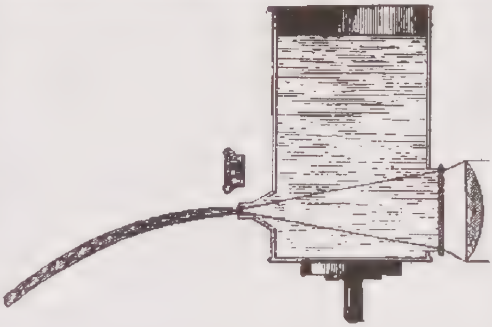


Fig. 349.

A further illustration of this is afforded by the experiment represented in fig. 350, by which light may be transferred from one part to another without illuminating the intervening space. In the

glass rod *a b*, if not too strongly curved, the light from *l*, entering at one of the plane ends, is repeatedly reflected at the inner sides of the rod, and emerges at the other end. The glass rod acts thus on the rays of light like a speaking-tube on sound waves.

Fig. 350.

356. **Mirage.**—The *mirage* is an optical illusion by which inverted images of distant objects are seen as if below the ground, or sometimes as if in the atmosphere. This phenomenon is of most frequent occurrence in hot climates, and more especially on the sandy plains of Egypt. The ground there has often the aspect of a tranquil lake on which are reflected trees and the surrounding villages. The phenomenon has long been known; but Monge, who accompanied Napoleon's expedition to Egypt, was the first to give an explanation of it.

It is a phenomenon of refraction, which results from the unequal density of the different layers of the air when they are expanded by contact with the heated soil. The least dense layers are then the lowest, and a ray of light from an elevated object, A (fig. 351), traverses layers which are gradually less

Fig. 351.

refracting; for, as we have shown (353), the refracting power of a gas diminishes with lessened density. The ray continues its path, being, however, more and more bent from one layer to the other, until the angle of incidence, which continually increases, reaches

the limit at which internal reflection succeeds to refraction (355). The ray then rises at O, as seen in the figure, and undergoes a series of successive refractions, but in a direction contrary to the first, for it now passes through layers which are gradually more and more dense, and therefore more refracting. The ray then reaches the eye in the same direction as if it had proceeded from a point below the ground, and hence it gives an inverted image of the object, just as if it had been reflected, at the point O, from the surface of a tranquil lake.

Mariners sometimes see in the air images of the shores, or of distant vessels. This is of more infrequent occurrence, but is due to the same cause as a mirage, though in a contrary direction: it occurs generally when the temperature of a stratum of the air is higher than that of the air below, for then total reflection may take place, and a ray from a ship or the distant shore enter the eye as if coming from a point in the sky. The images of distant objects which are visible to us in consequence of an unusual atmospheric

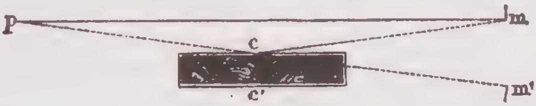


Fig. 352.

refraction and reflection in the air, may, when the density of the various layers changes irregularly, appear not only distorted, but even in continual motion. The best example of this is what is known as the *fata morgana*, which are often seen at Naples, Reggio, and on the coasts of Sicily. There are suddenly seen in the air at a great distance ruins, columns, palaces, castles, etc.—in short, a multitude of objects whose appearance is continually changing. This fairy-like phenomenon depends on the fact that objects become visible which are not so in the ordinary condition of the air, and which appear to be broken, distorted, and continually moving because the unequally dense layers of air are in a constant state of motion. Scoresby observed several such cases in the Polar Seas. To the same class of phenomena belongs the tremulous appearance of objects seen through the current of hot air arising from a chimney or a spirit-lamp. It is related that in this way clandestine stills have been detected by the revenue officers. Some of the stories of *second sight* may possibly have their origin in phenomena of this kind.

The *twinkling* or *scintillation* of the fixed stars is also to be accounted for by alterations in the direction of the motion of their light due to refraction in the atmosphere. It has been observed that this twinkling is especially marked when the air has been dry for a long time, and more aqueous vapour begins to diffuse, by which inequalities of density are produced ; thus a marked increase of the brightness of the twinkling is to seafaring people a sign of approaching rain.

The effect of the mirage may be illustrated artificially, as Dr. Wollaston showed, by looking along the side of a red-hot poker at a word or object ten or twelve feet distant. At a distance less than three-eighths of an inch from the line of the poker, an inverted image was seen, and within and witnout that an erect image. A better arrangement than a red-hot poker is a flat sheet iron box, about 3 feet in length by 5 to 7 inches in height and breadth (fig. 352) ; it is filled with red-hot charcoal and held at about the level of the eye. Looking over the lid of the box in the direction *pm* a *direct*, and in the direction *pm'* an *inverted*, image of a distant object, *m*, is seen. The same phenomenon is observed by looking along the sides.

Another instance which may be given is the observation of Sir Robert Ball, who, when on board ship, noticed the moon rise, he being in such a position that the line of sight grazed the funnel under an angle of 20° ; the appearance of its light reflected from the black surface was so brilliant as to suggest the idea that the reflection was from a highly polished mirror.

CHAPTER IV

EFFECTS OF REFRACTION THROUGH PRISMS AND THROUGH LENSES

357. **Media with plane parallel faces.**—When a pencil of light traverses a transparent medium, three cases may be considered. First, that in which the medium is comprised between two parallel planes; secondly, that in which it is comprised between two plane surfaces inclined towards each other; thirdly, that in which the medium is comprised between two curved surfaces, or between a curved and a plane surface, which gives rise to similar effects.

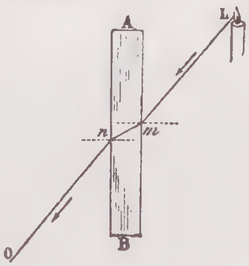


Fig. 353.

We will start with the consideration of the first case, and let L*m* be a ray of light traversing a glass plate, AB, with parallel faces (fig. 353). In passing from air into glass at the point *m*, this ray approaches the perpendicular; but as, on its emergence from the glass at the point *n*, it deviates from the perpendicular by exactly the same amount, it follows that, after having traversed the glass plate, its direction *n*O is exactly parallel to L*m*; whence we conclude that light is displaced, but not deviated, when it traverses a medium with parallel faces, such as the glass in our windows.

This holds only when the two surfaces are quite parallel and true planes, such as plate glass; seen through ordinary glass, objects often appear out of shape.

If a glass plate is placed over a sheet of paper on which are marked straight or curved lines, and they are looked at obliquely, a break is seen (fig. 354), which is not so when the lines are looked at perpendicularly (fig. 355).

358. **Prisms.**—A *prism* is the term applied in optics to any transparent medium comprised between two plane faces inclined

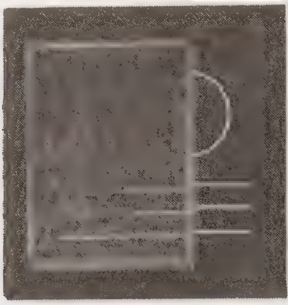


Fig. 354

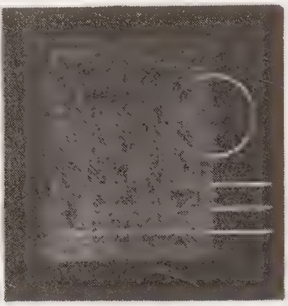


Fig. 355.

to each other. Thus the facets of a glass stopper taken in pairs form as many prisms.

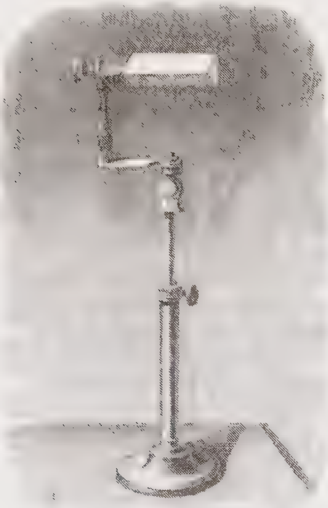


Fig. 356.

Fig. 356 represents the shape and arrangement of a prism for optical experiments. It is a piece of glass bounded by three plane faces, and its ends are equal and parallel triangular faces. The mass of glass thus cut may be turned about an axis parallel to its edges ; and it is, moreover, mounted on a stand with a double joint, so that it can be placed in any position whatever.

Prisms produce a remarkable effect upon light which traverses them. First a *deviation*, and second a *decomposition* into various kinds of light. Although these effects are always simultaneous, we shall examine the first by itself ; the second will be afterwards investigated under the head of *dispersion*.

359. **Path of rays in a prism.**—To trace the path of a ray of light in passing through a prism, let us suppose this cut by a plane perpendicular to its edges, and let *mno* (fig. 357) be the section thus obtained. If we consider the path of a ray of light, L*a*, along this section and meeting the prism at *a*, this ray approaches the perpendicular to the surface *mn*, and takes the direction *ab*. But on emerging from the prism it is again broken in the same direction, being deflected away from the perpendicular at the surface *mo*; for it passes into a less refracting medium. It forms then a broken line L*abc*; so that the eye which receives the ray, *bc*, which is called the

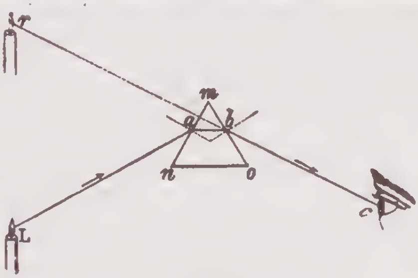


Fig. 357.

emergent ray, sees the object in the direction *cbr*—that is, raised towards the point *m* (335); which is expressed by saying that an object seen through a prism appears deflected towards the *summit*—that is, towards the edge which separates the faces of incidence and emergence.

The phenomenon is very easily demonstrated by observing any object whatever through a prism, as represented in fig. 357. The object appears to be raised when the summit of the prism is uppermost, and lowered when the summit is downward. If the prism is vertical, the image is displaced either to the right or to the left of the observer, according to the position of the refracting edge in either direction.

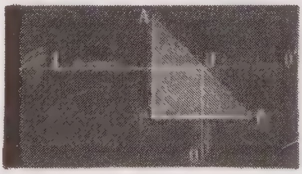


Fig. 358.

This property which prisms have, of twice deflecting the light in the same direction, forms the basis of what has to be said about lenses.

If we have a glass prism whose section, ABC (fig. 358), is a right-angled isosceles triangle, and if a ray of light, O, falls perpendicularly on the face CB, it will not be refracted; but it falls on the face AB, and, as can easily

be shown, makes with the face an angle of 45°. Now, this angle is greater than the critical angle of glass, which is rather less than 42°, so that the ray OH undergoes at H total reflection, and takes the direction HI, perpendicular to the face AC, so that the eye, looking along IH, sees the image O′ of the source from which the rays originally proceeded; the face AB producing the effect of the most perfect plane mirror.

This property of rectangular prisms is frequently made use of when it is desired to change the direction of rays with the least loss of light, as in the prismatic compass (422); it is also employed in apparatus for projection, where a phenomenon which takes place on a horizontal plate, like that in fig. 421, is to be shown on a vertical screen.

360. **Different kinds of lenses.**—In optics the name *lens* is given to masses of glass bounded by two spherical surfaces or by a plane and a spherical surface. The true lens, the only one to which the name is strictly applicable, is that in which both surfaces are bulged outwards, such as are represented in a side view in fig. 359, but this term of lens has been extended to other masses of glass, from the analogy of their action on light.

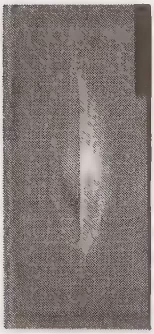


Fig. 359.

They are usually made either of *crown glass*, which is free from lead, or of *flint glass*, which contains lead, and has greater refractive power than crown glass (352).

The combination of spherical surfaces, either with each other or with plane surfaces, gives rise to six kinds of lenses, sections of which are represented in figs. 360, 361; four are formed by two spherical surfaces, and two by a plane and a spherical surface.

M is a *double convex*, N is a *plano-convex*, P is a *double concave*, Q is a *plano-concave*. The lens O and the lens R are called *meniscus* lenses, from their resemblance to the crescent-shaped moon; they are also called periscopic lenses (407). They are *convexo-concave* or *concavo-convex*, according to the face presented to the object.

The first three, M N and O, which are thicker at the centre than at the borders, are convex or *converging* lenses; the others, which are thinner in the centre, are concave or *diverging* lenses. In the first group the double convex lens, M, only need be con-

sidered, and in the second the double concave, P, as the properties of these lenses are in principle the same as all those of the corresponding groups.

361. **Principal axis ; optical centre ; secondary axis.**—Before describing the properties of double convex lenses, we must premise some definitions analogous to those already given for

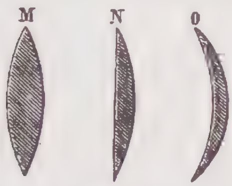


Fig. 360.

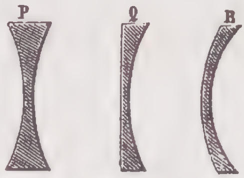


Fig. 361.

mirrors. A double convex lens is, as shown in fig. 362, the portion common to two spheres which intersect each other. That being understood, the centres, C and *c*, of these spheres are called the *centres of curvature* of the faces of the lens, and the straight line, XY, which passes through these points, is the *principal axis.*

Besides these two centres of curvature, there is a remarkable point in the lenses called the *optical centre.* The name is given to a point, O, on the principal axis equidistant from the two faces of the lens—at all events, when they have the same curvatures, which is the usual case. Now, it can be shown by geometrical considerations that any ray of light which passes through the optical centre emerges without deflection—that is, it comports itself just as if it traversed a medium with parallel faces (357)—while the luminous rays which do not pass through this point are deflected twice in the same direction, as in passing through prisms (359).

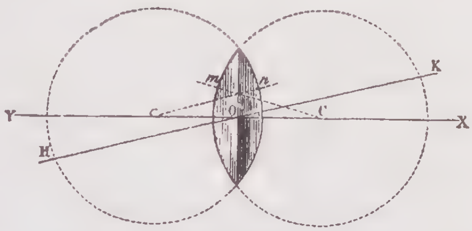


Fig. 362.

Any straight line, KH, which passes through the optical centres

without passing through the centres of curvature, is a *secondary axis.* There is only one principal axis, but the number of secondary axes is unlimited. We shall subsequently learn that the principal and the secondary axes play exactly the same part in the formation of images in lenses as they do in concave and convex mirrors.

On this assumption we may conceive, at the points of incidence and emergence, two plane surfaces, more or less inclined to each other, producing the same effect as a prism (fig. 363). We may then assimilate each of the lenses M, N, O (fig. 360) to a series of prisms joined at the bases, and the lenses P, Q, R (fig. 361) to a similar series joined in the opposite direction. This shows why the former should *converge* the rays and the latter *diverge* them, since a ray of light which has passed through a prism is deflected towards the base. Hence all convex lenses are *convergent*, and concave lenses *divergent.*

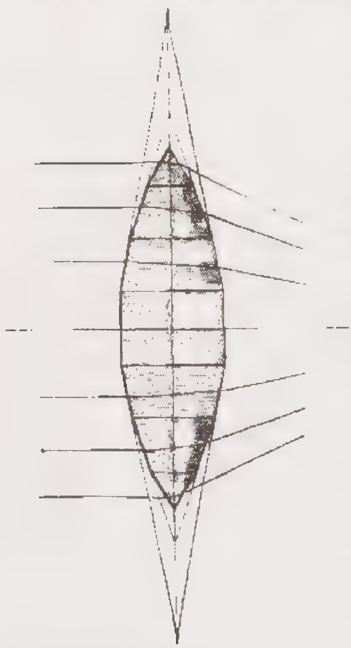


Fig. 363.

In order to compare the path of the luminous rays in a lens with that in a prism, the same hypothesis is made as for curved mirrors (343)—that is, the surfaces of these lenses are supposed to be formed of an infinity of small plane surfaces or elements ; the *normal* at any point is then the perpendicular to the plane of the corresponding element—at m, for instance (fig. 362), it is the straight line mC joining the point m to the centre of curvature ; in like manner, at n the normal is cn. This being premised, the properties of lenses are easily deduced from those of prisms (359).

362. **Path of rays in convex lenses. Foci.**—The rays of

light which enter a lens may be either parallel or divergent; we will first consider the former case, and suppose, further, that the rays are parallel to the principal axis, as is shown in fig. 364. From the above hypothesis, that the curved surface of a lens is an assemblage of small plane facets, or elements inclined towards each other, it will be seen that the ray X, which coincides with the principal axis, traverses the lens perpendicularly to the facets on entrance and emergence; and that, therefore, it continues to travel in a right line, as traversing in reality a medium with parallel faces. This, however, is not the case with any other ray, L, more or less distant from the principal axis; for here, the small facets at the points of incidence and emergence being inclined to each other like the faces of a prism, the ray is twice bent in the same direction, so as to cut the principal axis in a point F. Any other ray, M, is deflected in the same manner, and, although more distant from the

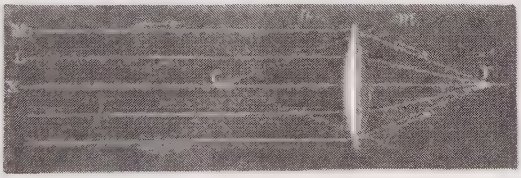


Fig. 364.

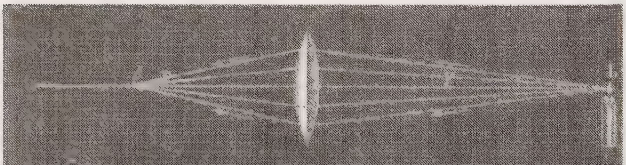
principal axis, will cut it at F; which arises from the fact that the two opposite facets at the points of entrance and emergence, being the more inclined to each other the nearer they are to the edges of the lens impart to the ray a greater deviation. All rays parallel to the axis behave in the same manner after having traversed the lens, and it can thus be understood how a parallel pencil is transformed into a converging pencil. The point where all the rays which were parallel to the axis coincide is called, as in the case ot mirrors, the *principal focus*, and we shall represent it by the letter F. It may be formed on either side of the lens, according to the direction in which light falls on the lens. The distance of either of the principal foci from the lens is called the *focal length* of the lens.

The focal length of a double convex lens is the shorter the greater the curvature of its faces. It depends also on the nature of the material of which the lens is formed; the greater the refractive index (351), the shorter is the focal length. Thus, a lens of

water, the refractive index of which is 1·334, would have a greater focal length than one of glass, whose refractive index is 1·5. A lens of diamond, the refractive index of which is 2·4, or of ruby, again, would have a shorter focus than one of glass ; supposing of course the curvatures of the faces to be the same in each case. A glass globe filled with water is sometimes used to concentrate the light of a lamp on an object, as in wood engraving.

The position of the principal focus of a convex lens is fixed, and is easy to determine ; nothing more is required than to receive on the lens a pencil of parallel rays—a pencil of sunlight, for instance—and then to hold behind the lens a sheet of white paper. By moving this, a position is found in which the luminous

Fig. 365



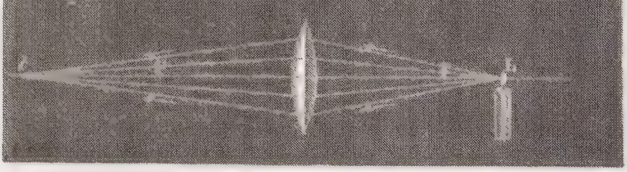


Fig. 366.

circle formed on the screen is least in size but brightest in lustre ; this point is the principal focus.

Where sunlight is not available, the principal focus may be determined by ruling a scale on paper, and then holding the lens between it and a movable screen. The ruled paper should be brightly illuminated by a lamp or otherwise. By varying the position of the lens and screen, a position is found by trial in which the object and its image are of the same size ; that is, the lines on the screen the same distance apart as those on the scale. Measuring then the distance between the image and the object, the focal distance of the lens is one-fourth of this.

363. **Conjugate foci.**—We will now consider the case in which

the source of light is at a small distance, but yet farther than the principal focus (fig. 365). The pencil which falls upon the lens being then divergent, it follows that, after having traversed the lens, the rays converge less rapidly than in fig. 364, and that, therefore, they no longer coincide in F, but beyond it, in a point *l*, which is called the *conjugate focus* of the point L, to express, as in concave mirrors (345), the correlation of these two points, which is of such a kind that when the luminous object passes from L to *l*, the conjugate focus conversely passes from *l* to L. Thus, L and *l* are *conjugate foci*; each is the focus of rays starting from the other.

The position of the conjugate focus is not fixed; it varies with that of the luminous object: the nearer this is to the lens, the more

Fig. 367

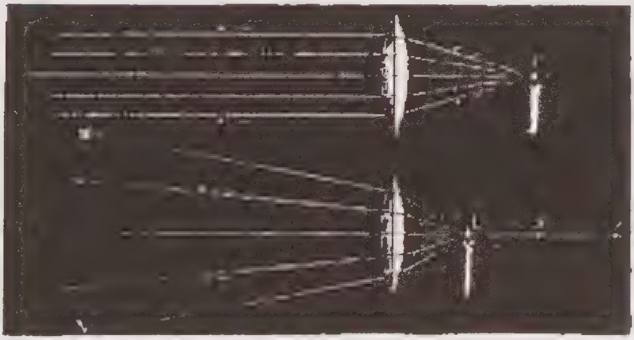


Fig. 368

distant is the conjugate focus, as shown by comparing fig. 366 with fig. 365; in fact, the incident rays being more and more diverging, the emergent rays are necessarily so too.

We will now consider the case in which the luminous object, coming continually nearer the lens, ultimately coincides with the principal focus (fig. 367). This being the point where rays parallel to the axis coincide, it follows, conversely, that luminous rays which start from this point pursue in the opposite direction the same path as in arriving—that is to say, that they form a pencil parallel to the axis on emerging from the lens, and that in this case no focus can be produced at any distance.

364. **Virtual focus.**—We have still to consider the case in which the refracted rays are divergent, *i.e.* do not meet in a real focus. Let us suppose that a luminous object, continually coming nearer the lens, ultimately comes between it and the principal focus (fig. 368). The divergence of the incident pencil being then greater than in fig. 367, it follows that the rays after emergence will be more and more spread out than in this figure; they should, therefore, become divergent, as shown in the pencil MN. The eye which receives these rays will suppose that they proceed from the point *l*, where their prolongations coincide; in this point the image of the luminous object will appear. It is then, however, only a virtual focus, just like that in a concave mirror, when the luminous object is placed between the mirror and its principal focus.

365. **Summary of the properties of convex lenses.**—From what has been said, we may deduce the three following principles as to the properties of double convex lenses:—

I. Rays of light parallel to the axis, after having traversed a double convex lens, converge to a single point, which is the principal focus (fig. 364); and, conversely, rays from this point form, on their emergence from the lens, a pencil parallel to the axis (fig. 367).

II. Rays of light emitted from a point outside the principa focus converge on emerging from the lens, and coincide in a point called the conjugate focus (fig. 365), which is formed at a greater distance behind the lens, the nearer the luminous obiect is to the principal focus (fig. 366).

III. Finally, the rays from a point between the lens and the principal focus diverge as they emerge, and give rise to a virtual focus on the same side as the object (fig. 368).

A knowledge of these properties of foci is requisite in explaining the formation of images by lenses.

366. **Real images produced by convex lenses.**—The refraction of light in double convex lenses gives rise to images, which are quite comparable with those seen by reflection in concave mirrors (347), and, like these, are of two kinds, *real* and *virtual.*

We will first consider the case of a real image. This is formed whenever any object is placed in front of a convex lens outside its principal focus; the lens reproduces then, on the other side, a reversed image of the object, which may be caught upon a screen (fig. 369), and is equally remarkable for the fidelity

of the colour and for the accuracy of the outlines; this is the real image. Its formation may be readily understood by reference to what has been said about conjugate foci (363). Yet it must be added that, as all the properties of the principal axis apply also to the secondary axis, it follows that, as a point on the principal axis has always its focus on this axis, so also any point on a secondary axis has its focus on the latter. Hence, in the figure below, all rays from the point A converge at *a* on the secondary axis through this point, and form the conjugate focus of this point —that is to say, its image. In like manner, the image of the point B is formed at *b*, and, as the same is the case for all points of the object, the result is a series of coniugate foci. These in their entirety constitute the image *ab*, which is inverted and smaller.

Fig. 369.

The reversal arises from the crossing of the secondary axes between the object and the image, and its smallness from its being formed nearer the lens than the object is.

Yet the image is not always smaller than the object; it may be larger. For, from the reciprocity between the position of the object and its conjugate focus (363), if, in fig. 369, *ab* were the object, then, as the luminous rays pursue the same path, but in the opposite direction, the image would be formed at AB, reversed as before, but larger. A convex lens may thus give real images, which are either smaller or larger than the object. This may be verified by the following experiment: A double convex lens is placed in a dark room, and in front of it, but some yards beyond the principal focus, a lighted candle. If then there is placed

behind the lens a screen, which can be moved more or less near, a position is found in which there is produced on the screen a very small and inverted image of the candle. If, on the contrary, the lens is brought nearer to the candle and at the same time the distance of the screen is increased, an inverted image is still obtained, but it is greatly enlarged, as shown in fig. 370.

This principle, that *convex lenses give real and very small images of distant objects*, and, on the contrary, *greatly magnified images of near objects*, will meet with numerous applications in the optical instruments which will be presently described. The apparatus represented in fig. 370 is convenient for investigating optical phenomena : it is known as the *optical bench.*

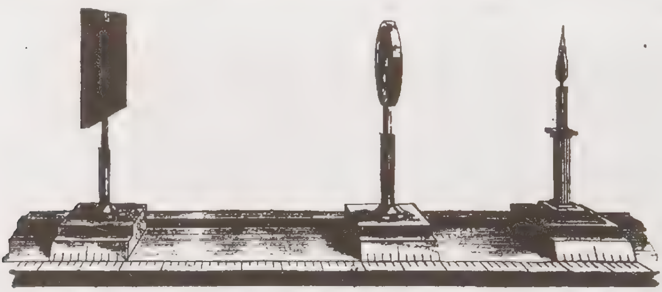


Fig. 370.

If we replace the lens by a concave mirror and interchange the position of the mirror and the light, the laws of the formation of images in concave mirrors may be investigated.

367. **Virtual images in convex lenses.**—Besides the real images we have just considered, convex lenses give also virtual images, which are produced under the same conditions as the virtual foci—that is, when the object is between the lens and the principal focus. For let an object, *ab* (fig. 371), be placed between a double convex lens and its principal focus, F ; applying here what was previously said in reference to virtual foci, we know that all rays proceeding from any point, *a*, of the object emerge while diverging, and reach the eye as if they proceeded from the point A, where the prolongations of the same rays coincide, and where there is formed for the eye the virtual image of the point *a*. For the same reason the eye sees at B the image of *b* ; hence the image of *ab* appears at AB, but it is virtual—that is to say, it does not really

exist, it could not be received on a screen, and is only an optical illusion.

It is to be remarked that, in opposition to what takes place when the image is real, the virtual image is erect, and in all cases larger than the object. The rectification of the image arises from the fact that the secondary axes do not intersect between the image and the object, but beyond it ; the magnification arises from the image being farther than the object from the point of intersection of the secondary axes which pass through *a* and *b*.

The term lens is applied to the lenticular glasses used as magnifying glasses. Every one is aware that if the print of a book be closely looked at through such a lens, it will appear larger ; if

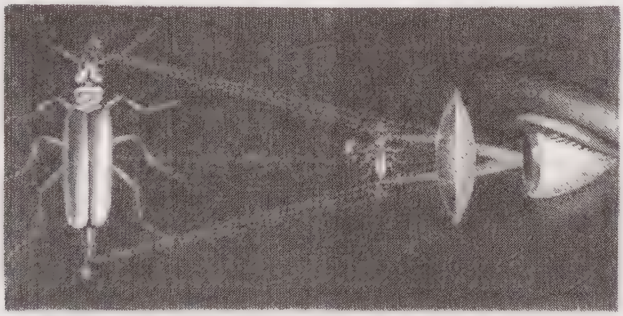


Fig. 371.

the lens be gradually removed, a position is reached when the printed characters disappear. This is the case when they are in the principal focus : when it is still farther removed, the characters reappear ; but they are reversed, for they are then beyond the principal focus.

368. **Double concave lenses ; foci and images.**—We have seen, in speaking about double convex lenses, that as the thickness decreases from the centre towards the edge, the small plane facets corresponding to the incidence and convergence of the same ray are more and more inclined from the centre to the periphery. But in double concave lenses, on the contrary, where the thickness increases from the centre to the edge, the small facets are more and more apart ; and hence the opposite phenomena. For, while double convex lenses cause the rays which traverse them to

coincide, by breaking them twice in the same direction, so as to bring them nearer the principal axis, double concave lenses produce the opposite effect, and only increase the divergence of the rays.

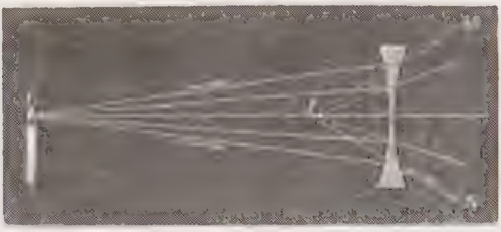


Fig. 372.

This may be readily understood by reference to fig. 372, in which it is apparent how the rays are twice broken in the same direction, so as to diverge from the axis and give rise to the

Fig. 373.

diverging pencil MN. But the eye which receives this pencil is acted upon by it as if the luminous object were at *l*; there is thus produced a virtual focus—the only one possible in concave lenses.

As these kinds of lenses have only virtual foci, they can produce none but virtual images ; these images are, moreover, always erect and smaller than the object. Thus, let AB be an object seen through a double concave lens (fig. 373) ; the pencil of light from A is deflected on passing through the lens, in such a manner as to reach the eye as if it were emitted from a point, *a*, on the secondary axis, AO. In like manner, the pencil from the point B reaches the eye as if it started from the point *b*. A virtual image of the object AB, which is smaller and erect, is formed, therefore, at *ab*, between the secondary axes AO and BO. This image is necessarily always smaller than the object, for it is nearer the point, O, where the secondary axes intersect.

369. **Refraction of heat.**—When a pencil of the sun's rays is received on a condensing lens, not merely is light concentrated on its focus, but heat also ; for a piece of an inflammable substance —such as tinder, paper, cloth, wood—placed in the focus, soon begins to burn.

This property which condensing lenses have is utilised for producing fire in what are called *burning-glasses*. The parallel rays of the sun falling on the condensing lens converge after refraction to the principal focus of the lens, where an image of the sun is formed, and may become dangerous by acting as a source of fire. The same danger may arise with spherical glass vessels filled with water, for they refract the light and heat like double convex lenses. Thus a vase for holding gold-fishes has been known to act as a burning-glass, setting fire to window-curtains near which it had been left in the sunshine. A drop of water, too, on a leaf, concentrates the sun's rays, and frequently marks the leaf.

The concentration of the heat-rays of the sun has received a curious application in certain sundials, when the hour of midday is marked by the discharge of a small cannon (fig. 374). Above the cannon is a condensing lens, the focus of which exactly corresponds to the *touch-hole* of the cannon the moment the sun passes the meridian of this place. Hence, the cannon being charged and primed beforehand, the lens ignites the powder just at midday, and the explosion announces the time at a distance.

The time thus given is what is called in astronomy *solar time*, or *true time*, in which the length of day varies. Now, our watches and clocks, being regulated for *mean time*—that is to say, for an unchangeable day—only agree with the sun four times a

year: December 24, April 15, June 15, and September 1. On February 11 a clock giving mean time is 14′ 37″ faster than the sun, and on November 3 it is 16′ 17″ slow. The *equation of time* represents the amount which on all the days of the year must be added to or taken from the time of a clock to obtain the true time. Hence, strictly speaking, it is incorrect to use the ordinary expression that a good watch or good clock goes like the sun.

The same principle is applied in the *sunshine recorder*, which consists essentially of a glass sphere on which the sun's rays fall, their image being received on a strip of millboard stretched in a frame at the proper focal distance. When the sun shines, a mark is burnt in the millboard, which is not the case when the sun sets or is hidden by a cloud. As the sun moves, the position of the

Fig. 374.

spot moves too, and thus we have a series of marks, or, where the sun shines continuously, a line.

Brewster described a lens three feet in diameter, and the rays after passing through it were received on a second lens 13 inches in diameter. The sun's rays were brought to a focus at a distance of 63 inches from the large lens, forming a small circle three-eighths of an inch in diameter. The heat here was so intense as to melt in a few seconds the most refractory metals.

370. **Lighthouses.**—*Lighthouses* built near the seashore or on detached rocks are intended to produce luminous signals visible at great distances, in order to guide mariners in darkness and enable them to keep clear of danger. Oil lamps were formerly used, placed in the principal focus of parabolic reflectors, which sent the reflected light to a great distance, its rays being parallel.

In 1822 Fresnel made a great improvement in the illumination of *lighthouses* by substituting for metal reflectors, which soon tarnished, large plano-convex lenses, in the focus of which he placed a powerful lamp with four concentric wicks, and equal in illuminating power and quantity of oil consumed to seventeen *Carcel* lamps (331). But the difficulty of constructing such lenses, which must necessarily be large, and which should at the same time not be thick, so as not to absorb much light, led Fresnel to adopt a special system of lenses, known as *échelon* or *lighthouse lenses.*

Fig. 375.

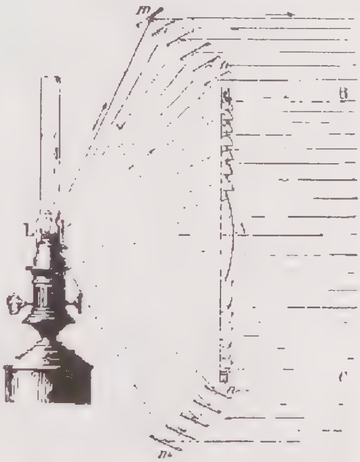


Fig. 376.

Seen in front in fig. 375, and in profile in fig. 376, they consist of a plano-convex lens, A, a foot in diameter, round which are arranged eight or ten glass rings, which are also plano-convex, and whose curvature is calculated so that each has the same focus as the central lens, A. A lamp is placed in the focus of this refracting system, and above and below the lenses are arranged silvered glass mirrors, *mn* ; thus the rays which would be lost towards the sky and the earth are utilised and sent in a horizontal direction. By this double combination a vast horizontal beam of light is obtained, which penetrates to a distance of 20 or 30 miles, but only in one direction. To increase the number of points

of the horizon at which the light may be seen, Fresnel, instead of a single system of lenses and mirrors represented in fig. 376, united eight such arrangements, so as to form an enormous glass pyramid with eight faces, as seen in fig. 377, which represents a

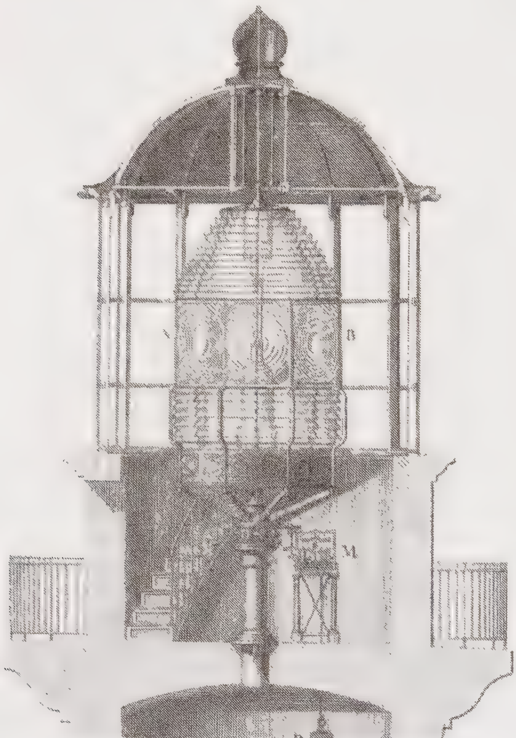


Fig. 377.

lighthouse lens of the largest size ; the system of mirrors and lenses alone is ten feet high.

A lighthouse lens of this kind sends a powerful beam of light towards eight points of the horizon, but all other points are destitute of light, so that vessels sailing in these dark parts would have

no help from the lighthouse. This difficulty was removed by Fresnel by means of a very simple mechanism, represented at the lower part of fig. 377. Clockwork, M, moved by a weight, P, imparts to the whole system of lenses, AB, a slow rotary motion. During a complete revolution of the apparatus, the whole horizon is successively illuminated, and the mariner, lost in the night, sees the light alternately appear and disappear after equal intervals of time. These alternations serve to distinguish the light of a lighthouse from a ship's light or a star. By means, too, of the number of times the light disappears in a given time, and by the colour of the light, sailors are enabled to distinguish lighthouses from one another, and hence to know their position.

Of late years the use of the electric light has in many lighthouses been substituted for that of oil lamps. A description of the apparatus will be given in a subsequent chapter.

CHAPTER V

DECOMPOSITION OF LIGHT BY PRISMS

371. **Solar spectrum.**—In speaking of prisms and lenses, we have only considered the change in direction which these transparent media produce in luminous rays, and the images which result therefrom ; but the phenomenon of refraction is by no means so simple as we have hitherto assumed : when *white* light, or that which reaches us from the sun, passes from one medium into

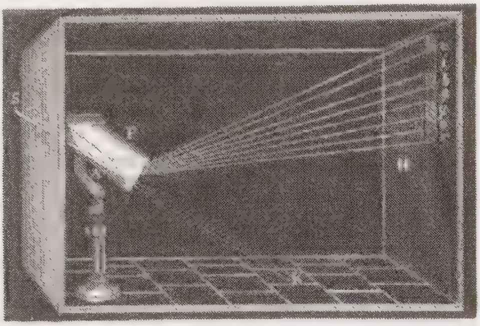


Fig. 378.

another, *it is decomposed into several kinds of light*, a phenomenon to which the name of *dispersion* is given.

In order to show that white light is decomposed by refraction, a pencil of the sun's rays (fig. 378) is allowed to pass through a small aperture in the window-shutter of a dark chamber. This pencil tends to form a round and colourless image of the sun on a screen ; but if a flint-glass prism arranged horizontally be interposed in its passage, the beam, on entering and emerging from

the prism, is refracted towards its base, and produces on a distant screen a vertical band *v*, *i*, *b*, *g*, *y*, *o*, *r*, rounded at the ends and coloured in all the tints of the rainbow. This coloured band is called the *solar spectrum*. In this spectrum, the production of which forms one of the most brilliant optical experiments, there is in reality an infinity of different tints, which imperceptibly merge into each other ; but, with Newton, it is customary to distinguish seven principal colours, as seen in the coloured plate. These are *violet*, *indigo*, *blue*, *green*, *yellow*, *orange*, *red* ; they are arranged in this order in the spectrum, the violet, *v*, being the most refrangible, and the red, *r*, the least so. They do not all occupy an equal extent in the spectrum, violet having the greatest extent, and orange, *o*, the least.

From the experiment ot the solar spectrum Newton concluded that *white* light—that is, light coming from the sun—is not *homogeneous* (that is, simple), but consists of seven different lights which, united, give the impression of white, while, when separated, each produces its own colour. He ascribed the separation of these seven lights in their passage through the prism to their different degrees of refrangibility. For if they were all equally refrangible, as they would be equally bent on entering and emerging from the prism, they would traverse it without being separated, and the light would be white on emerging as well as on incidence.

372. **The colours of the spectrum are simple.**—If one of the colours of the spectrum (the yellow, for instance) be isolated by intercepting the others by means of an opaque screen, and if the light thus intercepted be allowed to pass through a second prism, it is deflected, but without decomposition ; that is, it only gives rise to a single emergent pencil. As the same phenomenon is observed with the other colours of the spectrum, it is concluded that they are indecomposable by the prism, which is expressed by saying that the seven colours of the spectrum are *simple* or *primitive colours*. The light emitted from luminous bodies is seldom or never simple ; on being examined by the prism it will be found to contain more than one colour. In optical researches it is frequently of great importance to produce *homogeneous* or *monochromatic* light. Common salt in the flame of a Bunsen's lamp gives an orange yellow of very great purity. For red light, ordinary light is transmitted through glass coloured with sub-oxide of copper, which absorbs nearly all rays excepting the red.

As regards the cause in virtue of which one part of the spectrum

produces in us the sensation of red, another of yellow, another of orange, and so forth, the undulatory theory teaches us that it depends upon the number of vibrations per second performed by the molecules of the luminiferous ether (323). The number, which is very great, differs with each colour, and increases from red to violet; for the extreme red it is 458 millions of millions in a second, and for violet 727 millions of millions. As the velocity of propagation is the same for all the colours of the spectrum, but each corresponds to a different number of vibrations, it follows that the wave-lengths must vary with different colours. It may easily be calculated that in the case of red the length of the wave is 650 millionths of a millimetre, and for violet 412 millionths.

373. **Luminous, heating, and chemical effects of the spectrum.**—The various spectral rays differ not only in their colour, but also in their luminous power, in their heating power, and in the chemical effects to which they give rise. It is found that the rays of medium refrangibility, the yellow and the green, illuminate the most powerfully. Thus, the print of a book placed in the yellow pencil is seen more distinctly than in the red or violet.

The heating action of the spectrum is demonstrated by successively placing a very delicate thermometer, or preferably a linear thermopile (Book VIII., chapter xiii.), in the various parts of the spectrum. It is observed that the heat attains its greatest intensity in the red, or rather a little beyond it. The existence of these invisible heat-rays, which are the least refrangible of the spectral rays, was discovered by Sir J. Herschel.

Passing from the heating action of light to its chemical action, we find that it tends to destroy most vegetable colours, such as wall-papers and dyed stuffs, which rapidly fade if exposed to bright light. Some chemical substances are known which are naturally white, and are blackened by the luminous rays, on which property depends the art of photography; there are mixtures of gases also, such as that of hydrogen and chlorine, which suddenly explode when exposed to the sun's rays. These chemical effects are not produced equally in all the parts of the spectrum; the greater chemical action is met with in the violet, and even a little beyond.

Fig. 379 represents the distribution of the heating, the luminous, and the chemical action of the spectrum; the shaded lines representing the parts of the spectrum not visible to the eye, which extend in both directions to a greater distance than is represented in the figure. The curve I represents the heating effect of

the spectrum, from which it will be seen that it is greatest at a little distance outside the visible red; the curve II represents the intensity of the light, which is greatest near Fraunhofer's line D in the yellow (374); the greatest chemical, or, as it is sometimes called, *actinic*, action is, as follows from the form of the curve III, just about the violet in the visible part of the spectrum. The invisible rays beyond the violet are known as the *ultra-violet rays*.

There is no essential difference between light rays, heat rays, and actinic rays. They are all physically the same, differing only in respect of wave-length. The eye is only capable of being acted on by waves whose wave-length lies between certain limits—those of the prismatic spectrum. These are called luminous rays. Rays whose wave-lengths are outside these limits, too great or too small, do not affect the eye. The short waves most powerfully affect a photographic plate. They are called actinic rays. The shorter the wave, the greater the refrangibility of the ray. The long waves corresponding to the rays beyond the visible red of the spectrum have the most powerful heating effects. Strictly speaking, we ought not to talk of light or heat as coming from the sun. The radiation from the sun consists of waves of all manner of lengths, from very small to very large. Such radiation falling on the blackened bulb of a thermometer is entirely absorbed, and manifests itself as *heat* only. If the radiation fall on a photographic plate, the plate, as it were, picks out the short waves and is chiefly acted on by them; but plates can be made so sensitive as to be susceptible to the action of red rays, and even those beyond the red. We may say, then, that solar radiation is neither heat nor light nor chemical action, but any one of these, according to the nature of the receiver on which it falls.

374. **Dark lines of the spectrum.**—The colours of the solar spectrum are not perfectly continuous, but the spectrum is crossed throughout its whole extent by a great number of very narrow, dark, transverse lines. They are best observed when a beam of sunlight is admitted into a darkened room through a narrow slit. If, at a distance of three or four yards, we look at this slit through a flint-glass prism, with its edge held parallel to the slit, we observe a number of very delicate dark lines parallel to the edge of the prism and at very unequal intervals.

The existence of these dark lines was first observed by Wollaston in 1802; but Fraunhofer, a celebrated optician of Munich, first

studied and gave a detailed description of them. He mapped the lines, and denoted the most marked of them by the letters A, *a*, B, C, D, E, *b*, F, G, H; they are therefore generally known as *Fraunhofer's lines.*

The dark line A (see fig. 1 of the Plate, p. 444) is towards the end, and A in the middle, of the red; C is in the red, but rather nearer the orange; D is in the orange, E in the green, F in the transition from green to blue, G in the indigo, H in the violet. There are certain other noticeable dark lines, such as *a* in the red and *b* in the green. In the case of the sun's light the positions of the dark lines are fixed and definite; in the spectra of the fixed stars the relative positions of the dark lines vary. For the electric light there are bright lines instead of dark ones; and in coloured flames—that is to say, flames in which certain chemical substances

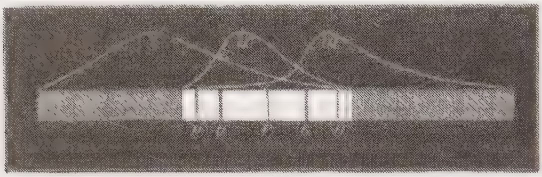


Fig. 379.

are being evaporated—the dark lines are replaced by very brilliant lines of light, which differ with different substances.

375. **Spectrum analysis.**—This property of coloured flames was first discovered by Sir John Herschel, who remarked that by volatilising substances in a flame a very delicate means is afforded of detecting certain ingredients by the colours they impart to certain parts of the spectrum; and Fox Talbot, in 1834, suggested optical analysis as probably the most delicate means of detecting minute quantities of a substance. To Kirchhoff and Bunsen, however, is really due a method of basing on the observation of these lines a method of analysis. They ascertained that salts of the same metal, when introduced into a flame, always produce lines which are identical in colour and position, but different in colour, position, or number for different metals; and, finally, that an exceedingly small quantity of metal suffices to disclose its existence. Hence has arisen a new method of analysis known as *spectrum analysis.*


A a B C D E b F G H
I
II
III
IV
V

376. **Spectroscope.**—The name *spectroscope* has been given to the apparatus used by Kirchhoff and Bunsen for the study of the spectrum. One of the forms of this apparatus is represented in fig. 380. It consists of three telescopes, mounted on a common foot, whose axes converge towards a prism, P, of flint-glass. The telescope A is the one through which the spectrum is observed ; it is *focused* by means of the milled-head screw *m*. The telescope B, called the *collimator*, has a slit at one end and a convex lens at the other, the slit being at the principal focus of the lens. *k* is

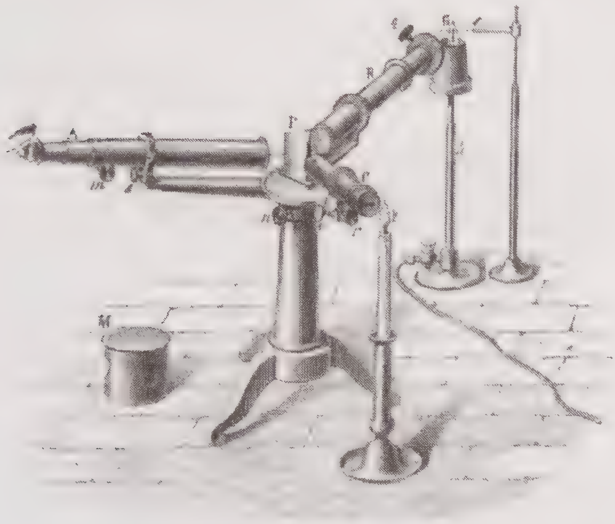


Fig. 380.

a *Bunsen's burner*, in which coal gas is burned, mixed with air in such a manner that a flame of little or no luminosity, but of great heat, is produced. The substance to be examined is placed in this, either in a solid form or in a state of solution, or on platinum wire at the end of the support *c*. It is thus volatilised by the intense heat, and the flame G is coloured. The rays emitted by this flame pass through the slit and the lens, so that on emerging they form a parallel pencil of rays, which falls on the prism P. Here they are refracted and decomposed, and form a spectrum,

which can be seen by an observer on looking through the telescope A.

The tube C has a different function; it contains a micrometric scale photographed on glass so that it is white on a dark ground. The light from the candle, F, passing through the scale and the lens in C, falls in parallel rays *on the face* of the prism P, and is *reflected* thence through the object-glass of A, so that the observer, seeing the spectrum and the scale simultaneously, can exactly measure the relative positions of the various spectral lines. M is a metal cap with three apertures, which covers the prism so as to exclude the diffused light.

Prisms of different substances may be combined in such a way that the incident light, though refracted and decomposed, preserves on the whole its original direction and produces a spectrum.

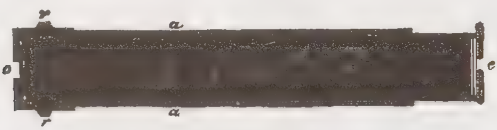


Fig. 381.

Combinations of prisms of this kind are used in what are called *direct-vision spectroscopes*. Fig. 381 represents the section of such an instrument in about $\frac{2}{3}$ the natural size. A system of two flint and three crown glass prisms is placed in a tube which moves in a second one; at the end of this is an aperture, *o*, and inside it a slit the width of which can by a special arrangement be regulated by simply turning a ring *r*. A small achromatic lens is introduced at *aa*, the focus of which is at the slit, so that the rays pass parallel through the train of prisms, and the spectrum is viewed at *e*.

Such apparatus are extremely convenient, and are indispensable in observing the spectra emitted by bodies which rapidly change their place, such as falling stars. For astronomical purposes they are constructed of suitable dimensions and fitted to telescopes.

377. **Experiments with the spectroscope.**—The coloured plate, page 444, shows certain spectra observed by means of the spectroscope. Fig. I. represents the solar spectrum.

Fig. II. shows the spectrum of *potassium*. It is *continuous*—that is, it contains all the colours of the solar spectrum. Moreover, it is marked by two bright lines one in the extreme red, corre-

sponding to Fraunhofer's dark line A; the other in the extreme violet.

Fig. III. shows the spectrum of ***sodium***. This spectrum contains neither red, orange, green, blue, nor violet. It is marked by a very brilliant orange-yellow ray in exactly the same position as Fraunhofer's dark line D. Of all metals, sodium is that which possesses the greatest spectral sensibility. In fact, it has been ascertained that one-two-hundred-millionth of a grain of common salt is enough to cause the appearance of the yellow line of sodium. Consequently it is very difficult to avoid the appearance of this line. A very little dust scattered in the apartment is enough to produce it, which shows how abundantly sodium is diffused throughout nature.

Figs. IV. and V. show the spectra of ***cæsium*** and ***rubidium***, metals discovered by Bunsen and Kirchhoff by means of spectral analysis. The former is distinguished by two blue lines, the latter by two very brilliant red lines and by two less intense violet lines. A third metal, ***thallium***, was discovered by the same method by Sir William Crookes in England, and independently by M. Lamy in France. Thallium is characterised by a single green line.

Subsequently to this Richter and Reich discovered a new metal associated with zinc, which they call ***indium***, from a couple of characteristic lines which it forms in the indigo. Boisbaudran discovered a new metal which he called ***gallium*** associated with zinc in very minute quantities. Quite recently Ramsay has discovered in the mineral *cleevite* a substance giving a line near the sodium which had hitherto been only found in the solar spectrum; it was hence known as the ***helium*** line. The substance ***helium*** is a gas.

The extreme delicacy of the spectrum reactions, and the ease with which they are produced, constitute them a most valuable help in qualitative analysis. It is sufficient to place a small portion of the substance under examination on platinum wire, as represented in fig. 380, and compare the spectrum thus obtained either directly with that of another substance, or with the charts in which the positions of the lines produced by the various metals are laid down.

With other metals the production of their spectra is more difficult, especially in the case of some of their compounds. The heat of a Bunsen's burner is insufficient to vaporise the metals, and a much higher temperature must be used. This is obtained by taking electric sparks between wires consisting of the metal whose spectrum is required, and the electric sparks are most conveniently

obtained by means of Ruhmkorff's coil (556). Thus all the metals may be brought within the sphere of spectrum observation.

The spectroscope has proved a most powerful instrument of research in astronomical investigation, and has led to most important conclusions respecting many celestial phenomena. An account of them is, however, inconsistent with the scope of this work.

Fig. 382.

378. **Recomposition of white light.**—Not merely can white light be resolved into lights of various colours, but, by combining the different pencils separated by the prism, white light can be reproduced. This recomposition may be effected in various ways.

I. A pencil of solar light is decomposed by a prism, as shown in fig. 382, and the spectrum is received, not on a screen, but on a rather large double convex lens in the focus of which is placed a small cardboard or ground-glass screen. The seven colours of the spectrum coincide in the focus, and here is formed on the screen a

perfectly white circular image, which shows that the union of the seven lights of the spectrum reproduces white light.

II. The same result is attained by replacing the double convex lens in the preceding experiment by a concave mirror. The seven coloured pencils being reflected from this mirror, there is formed in the focus the same white image as in that experiment.

III. By means of Newton's disc it may be shown that the combination of the seven colours of the spectrum forms white. This is

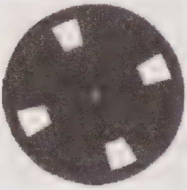
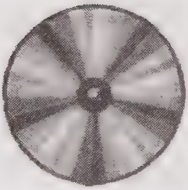


Fig. 384.



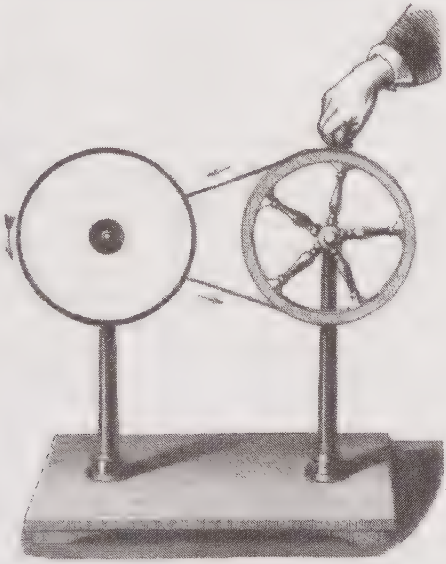


Fig. 383.

a cardboard disc of about a foot in diameter (fig. 383); the centre and the edge are covered with black paper, while in the space between there are pasted strips of paper of the colours of the spectrum. They proceed from the centre to the circumference, and their relative dimensions and tints are such as to represent five spectra. When this disc is rapidly rotated, by means of the turning table represented in fig. 383, it appears white, or at all events of a greyish white; for the colours which cover it cannot be arranged

exactly in the same proportions as those of the spectrum, nor are the tints so pure.

To explain this phenomenon let us observe that the impression produced upon the eye by the sight of a luminous body lasts a certain time after the cause which produced it has ceased. Thus, if a lighted stick be rapidly swung round, a circle of light is produced, which shows that the sensation produced upon the eye lasts after the stick has passed from in front of this organ. A harp-string while vibrating as it sounds appears like a thin transparent ribbon; a skyrocket in its rapid ascent appears like a line of light. Thus, too, in the above experiment, the disc is turned so rapidly that the action of the seven colours is virtually simultaneous, and the eye is affected as if it received them all together, and the disc therefore appears white.

379. **Zoetrope. Phenakistoscope.**—Several interesting experiments depend on the fact that the impression produced on the retina lasts after the cause producing it has ceased to act: such are the *zoetrope*, or wheel of life; the *thaumatrope*, or magical disc; the *phenakistoscope*, or deceiving disc. This last consists of a disc near the edge of which are a series of equidistant apertures; and on corresponding parts of a circle near the centre is depicted an object such as a rider on horseback, a bird flying, etc., in various stages of its motion. If the disc is made to rotate rapidly, while the picture side is held in front of a mirror, the eye, on looking through the apertures, no longer sees the separate stages; on the contrary, they all insensibly merge into each other, and coalesce to form a single impression, which is that of an actually moving body.

The *zoetrope*, or *wheel of life*, is very convenient for representing a number of vibratory motions. It consists of an open cylinder which can be rotated about its vertical axis, and has a number of vertical slits at the top. If the successive positions of a vibrating pendulum, for instance, are drawn on a narrow strip of paper, equal in length to the circumference, and this is placed inside the cylinder, when the wheel is rapidly rotated, on looking through the slits the pendulum seems as if it were steadily vibrating.

In the *kinematograph* a rapid succession of moving objects are taken by instantaneous photography, and their images, sharply illuminated, are successively projected in the same order on a screen which allows a certain fixed short time of exposure to each

picture before the next picture appears. In this way the most interesting and varied phenomena are vividly reproduced with lifelike accuracy.

If two threads are fixed to the edges of a cardboard disc, it can be rapidly rotated so that the two sides are alternately seen in rapid succession. If a broad black band is drawn on one side and a similar one is drawn at right angles to it on the opposite side, as represented in fig. 385, on rotating the disc the appearance of a cross is seen. If on one side a bird and on the other a cage are drawn, when the disc is rapidly rotated the bird appears in the cage, etc.

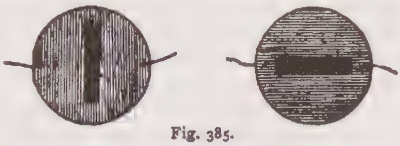


Fig. 385.

A certain duration of a luminous impression is necessary to produce an effect on the retina; hence it is that we do not see a very rapidly moving object, such as a bullet fired from a gun.

To this class of phenomena belongs also the fact that when a brightly illuminated jet of water is looked at through a rotating disc in which are a number of radial slits (fig. 384), the jet, instead of appearing continuous, seems as if made up of a number of individual drops.

380. **Newton's theory of the composition of light and the colour of bodies.**—Newton was the first to decompose white light by the prism, and to recompose it. From the various experiments which we have described he concluded that white light was not homogeneous, but formed of seven lights unequally refrangible which he called *simple* or *primitive* lights.

He was further led to the conclusion that bodies are not of themselves coloured—that is, have no colour of their own—but that they have the property of decomposing the white light which illuminates them, and of reflecting unequally the various kinds of light of which it is formed. Thus, vermilion is not red of itself, but is endowed with the property of reflecting red light and of absorbing all others, or, at any rate, of only reflecting them in far less proportion. In like manner the leaves of plants are not truly green; they have merely a greater reflecting power for green than for any other colour. In short, bodies are only coloured by the light they reflect. For, let these same green leaves be placed in a spectrum projected in a dark room: if they are in the green band they will appear of a dazzling green, far brighter than their natural colour; but if they

are placed in the red or in the violet they will appear black, for the reason that they absorb both red and violet rays, and only reflect green. A similar effect is produced if a rose be successively placed in each of the spectral bands, showing that the colours of bodies are not peculiar to them, but depend upon the kind of light which their molecular constitution gives them the power of absorbing and reflecting. In speaking, too, of the *green* or the *red pencil*, we do not mean that they are coloured of themselves, but merely that they have the power of producing in us the sensation of green or of red. The eye judges colours as the ear judges sounds ; both the colours and the sounds depend on the frequency of vibration of the particles of the media by which light and sound respectively are transmitted.

Bodies which reflect all colours in the spectrum equally well are white, those which reflect none at all are black ; so that black is not really a colour, but the absence of colour.

The varied shades which coloured bodies present result not merely from the fact that they simultaneously reflect various kinds of light, but from the fact that they reflect them to different extents. Thus, a body which reflects yellow and blue light will be green, but a green the shade of which varies with the quantities of yellow and blue light which the body reflects. If, by means of an opaque screen, part or all of certain colours of the spectrum be intercepted, and the others be united by means of a lens, as shown in fig. 382, there is no shade in nature which cannot be reproduced, but with a lustre and richness of colour which artificial pigments can never attain.

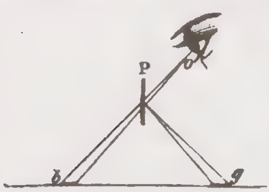


Fig. 386.

The simplest way of mixing coloured light is shown in fig. 386. P is a small flat piece of glass, *b* and *g* are two coloured wafers. The observer looks through the glass plate at *b*, while the coloured light from *g* is reflected from this glass ; if *g* be placed in a proper position, which is found by trial, its image nearly coincides with that of *b*. It then appears as if there were a single wafer at *b* with a colour produced by the mixture of the two real ones. In this experiment the light from *b* which traverses the glass actually unites with that from *g*, which is reflected from it, and the two combined pass on to the retina at *o*.

381. **Colours of transparent bodies.**—We have seen above that

opaque bodies owe their colour to the power of decomposing light by surface absorption, and of reflecting certain colours more abundantly than others. It is owing to the decomposition of light that transparent bodies seem to be coloured; though here the absorption is effected throughout the mass and not at the surface only. If all the rays of the spectrum were equally transmissible by transparent media, they would necessarily be colourless; that, however, is never quite the case—at all events, when the media have a certain thickness; for then they absorb certain colours of the spectrum more than others, and have the tint of the more transmissible colour. Water, for instance, seen by transmission through a great thickness, has a greenish tint, which shows that, of all colours contained in white light, it allows green to pass most easily.

Air, in great thickness, gives a bluish tint to distant objects, which would rather tend to prove that air is more transparent for blue than for any other spectrum colour. It is more probable, however, that this effect is due to the presence of the aqueous vapour in the air.

382. **Complementary colours. After-images.**—If one or more colours be suppressed in white light, when decomposed by the prism, the residue corresponds to one of the tints of the spectrum; and the mixture of the colours taken away produces the impression of another spectral colour. Thus, if in fig. 382 the red rays are cut off from the lens, the light on the screen is no longer white, but greenish blue. In like manner, if the violet, indigo, and blue of the colour-disc be suppressed, the rest seems yellow, while the mixture of that which has been taken out is a bluish violet. Hence white can always be compounded of *two* tints; and two tints which together give white are called *complementary colours.* Thus, of spectral tints, *red* and *greenish blue* are complementary to each other; so are *orange* and *Prussian blue*, *yellow* and *indigo blue*, *greenish yellow* and *violet.*

A distinction must be made between *spectrum colours* and *pigment colours.* Thus, a mixture of pigment yellow and pigment blue produces green and not white, as is the case when the blue and yellow of the spectrum are mixed. The reason of this is that in the mixture of pigments we have a case of the subtraction of colours, and not of addition. For the pigment blue in the mixture absorbs almost entirely the yellow and red light, and the pigment yellow the blue and violet light, so that only green remains.

Effects of complementary colours are met with in many curious

experiments. Thus, let any coloured object—a wafer, for instance—be placed on a black ground, and let it be viewed for some minutes until the sight is fatigued ; if then the eyes be turned to a sheet of white paper, an image will be seen of the same form as the object, but of the complementary colour—that is, if the wafer is red, its image will be green ; if it is orange, the image will be blue ; and so forth. In like manner, if, after looking for some time at the setting sun, the eye be turned to a white wall, an intense green disc will be seen, which lasts for some minutes, after which the red image appears ; a second green image succeeds to it, and so on for a great number of times, until the appearance fades away.

These images, which thus persist some time after an object has been looked at, and which have the complementary colours to those of the object, are called the *after-images*, or after-colours.

There is another kind of after-colour : when a coloured object placed on a white ground is attentively looked at for some time, the object is seen to be surrounded by a colour which is complementary to that of the object. This phenomenon, which is known as the *accidental halo*, is easily verified by means of a coloured wafer placed on a sheet of white paper.

These are known as *subjective* phenomena, because they do not belong to the object itself, but have their origin in the structure of the eye itself. Our judgment as to colour is greatly influenced by *contrast*. A gas flame, whose light, seen by itself, appears white, appears reddish in twilight or moonlight, and most of all by the light of the electric arc. If light is admitted into a dark room through two small holes near each other in a shutter, two bright spots are produced. If one aperture is closed with a red glass, the white spot arising from the other aperture appears green, and *vice versâ*.

When several pieces of cloth of the same colour are successively looked at, it will be seen that the later ones appear of a bad shade. This arises from the fact that the eye becomes fatigued ; the accidental colour of the cloth begins to form, and its own tint loses its brightness. So, too, when designs are printed or cloth is embroidered on a coloured ground, effects may be obtained quite different from those which were desired. Generally, if two adjacent colours are complementary, each will acquire a greater lustre and produce a pleasing impression ; but if they are of the same tint, they will mutually enfeeble each other. It will thus be seen how numerous are the applications which the phenomenon of accidental

images presents in combining colours in pictures, wall-papers, tapestry, furniture, and even in dress, although in this respect good taste has long been in advance of the data of science.

383. **Irradiation.**—This is a phenomenon in virtue of which white objects, or those of a very bright colour, appear, when seen on a dark ground, larger than they really are. Thus, a white square upon a black ground seems larger than an exactly equal black square upon a white ground (fig. 387). With a black body on a bright ground, the converse is the case. Again, a platinum wire made red-hot by the passage of an electric current seems far thicker than it is in reality. Irradiation is held to arise from the fact that the impression produced on the retina extends beyond the outline of the image. It bears the same relation to the space occupied by the image that the duration of the impression does to the time during which the image is seen.

Fig. 387.

The effect of irradiation is very perceptible in the apparent magnitude of stars, which may thus appear much larger than they really are; also in the appearance of the moon when two or three days old, the brightly illuminated crescent seeming to extend beyond the darker portion of the disc, and hold it in its grasp.

Plateau, who investigated this subject, found that irradiation differs very much in different people, and even in the same person on different days. He also found that irradiation increases with the lustre of the object and the length of time during which it is viewed. It manifests itself at all distances; diverging lenses increase it, condensing lenses diminish it.

384. **Rainbow.**—The *rainbow* is a luminous phenomenon which appears in the sky opposite the sun when rain is falling. It contains seven concentric arcs, presenting successively the colours of the solar spectrum. Generally only a single bow is perceived, but sometimes there are two; a lower one, the colours of which are very bright, and an outer or *secondary* one, which is much paler, and in which the order of the colours is reversed. In the interior rainbow, the red is the highest colour; in the other rainbow the violet is. It is seldom that three bows are seen; theoretically, a greater number may exist, but their colours are so enfeebled that they are not perceptible.

The phenomenon of the rainbow is produced by the decom-

position of the white light of the sun when it passes into the drops, and by its reflection from their inside face. In fact, the same phenomenon is witnessed in dewdrops and in jets of water, in the fine drops of spray of a waterfall, or those thrown up by the paddles of a steamer—in short, wherever the sun's light passes into drops of water under a certain angle.

The appearance and the extent of the rainbow depend on the position of the observer, and on the height of the sun above the horizon; hence only some of the rays refracted by the raindrops, and reflected in their concavity to the eye of the spectator, are

Fig. 388.

adapted to produce the phenomenon. Those which do so are called *effective rays.*

To get a general idea of this, let us refer to fig. 388, in which two raindrops, *a* and *c*, are represented extremely magnified as compared with the arc of which they form part. The pencil of white light which falls upon *a* is refracted on entrance into the droplet and decomposed, giving rise to seven rays, red, orange, yellow, green, blue, indigo, and violet (371). At the point *a*, on the posterior face of this droplet, a portion of the refracted light escapes, and is dispersed in the atmosphere without giving rise to any particular phenomenon; the light which has not emerged from the droplet is

reflected at *a*, returns and emerges on being a second time refracted, and reaches the observer's eye as represented in the figure.

A second droplet, *c*, placed below the preceding one, produces just the same effect, yet it does not send the same colour to the spectator. For, as the different colours are unequally refrangible, the coloured rays which emerge from the same raindrop diverge, and therefore are not propagated together, whence it follows that each drop only sends one kind of colour towards the observer. But, from the different degree of refrangibility of each ray, the droplets on the outside of the arc send only red rays towards the eye, and those on the inside violet rays. The other colours arise from intermediate droplets.

In short, the rainbow is the circumference of the base of a cone, the apex of which is the observer's eye, and the surface of this cone is formed from the outside to the inside of seven successive envelopes, red, orange, yellow, etc., corresponding to each of the bands of the spectrum. The nearer the sun is to the horizon, the larger is the visible part of the rainbow ; but, as the sun rises, the arc diminishes, and entirely disappears when the sun is 42 degrees above the horizon. A line drawn from the sun to the centre of the bow passes through the eye of the observer. Hence the rainbow is never seen except in the morning and evening, or, in rare cases, near midnight, when a full moon is low in the south.

CHAPTER VI

EFFECTS OF COLOUR IN LENSES. ACHROMATISM

385. **Chromatic aberration.**—In speaking of single lenses we have not mentioned a serious defect which they possess, which is, that objects seen through them at a certain distance seem surrounded by an iridescent fringe, which fatigues the sight and greatly diminishes the sharpness of the images.

For, as lenses may be compared to a series of prisms with infinitely small faces, and united at their bases, they not only refract

Fig. 389.

light, but also decompose it like a prism. On account of this dispersion, therefore, lenses have really a distinct focus for each separate colour. In a condensing lens, *db*, for example, the red rays, *d* R *r*, and *b* R *r'*, which are the least refrangible, form their focus at a point R on the axis of the lens (fig. 389), while the violet rays *b* V *v'* and *d* V *v*, which are most refrangible, coincide in the nearer point, V. The foci of the orange, yellow, green, blue, and indigo are between these points. Hence a double convex lens tends to give seven images, differently coloured, of objects seen through it. These images being partly superposed, the seven colours combine in the centre to form white light, but on the contours the extreme colours of the spectrum are visible—that is, more especially red and blue.

Hence, if a white screen be placed at *mn*, nearer the lens than

its principal focus, we shall have a bright circle surrounded by a red edge ; while if the screen is placed at *rs*, which is farther than the focus, the circle will have a blue edge.

This injurious coloration of the images is called *chromatic aberration.*

The inequality in the refraction of the blue and red rays may be demonstrated by closing a small aperture, half with red and half with blue glass (fig. 390) ; on each half a black arrow is painted, and a lamp is placed behind it. By means of a lens 2 feet focal length, an image is formed on a screen at a distance of about 7 feet. If the screen be placed so that a sharp image is obtained of the black object on the blue ground, the outlines of the other are confused. To get a sharp image of the arrow on the red ground, the screen must be moved farther away.


Fig. 390.

386. **Achromatic lenses.**—By observing the phenomenon of the dispersion of colours in prisms of water, of oil of turpentine, and of crown glass, Newton was led to suppose that dispersion was proportional to refraction. He concluded that there could be no refraction without dispersion, and therefore that achromatism was impossible. Almost half a century elapsed before this was found to be incorrect. Hall, an English philosopher, in 1733, was the first to construct achromatic lenses, but he did not publish his discovery. It is to Dollond, an optician in London, that we owe one of the greatest improvements which have been made in optical instruments. In 1757 he combined two lenses, one a double convex *crown glass* lens, the other a double concave lens of *flint glass* (fig. 391), a kind of glass which contains a good deal of lead, and which has greater dispersive power than crown glass.


Fig. 391.

By suitably choosing the curvatures of these two lenses, they may be made equally dispersive ; and as the dispersion is in opposite directions, one of the lenses being convergent and the other divergent, two effects are produced, which compensate each other as regards coloration, but not as concerns refraction—that is, a beam of white light which has traversed such a compound lens emerges colourless, but converging and forming a single focus on the axis.

The lenses thus formed of flint and crown glass give images which are not coloured on the edges ; they have hence been called *achromatic* lenses—*achromatism* being the term applied to the phenomenon of the refraction of light without dispersion.

387. **Spherical aberration.**—Chromatic aberration is not the only defect which lenses present : they have another, which is known as *spherical aberration*, and which arises from the fact that, apart from dispersion, the rays which traverse a condensing lens do not exactly converge to a single focus. Those which traverse the lens near the edges, VV′ (fig. 392), are more refracted than those which traverse the central part ; hence the former rays converge at F, nearer to the lens than the latter, which meet at G, in consequence of which the images are distorted.

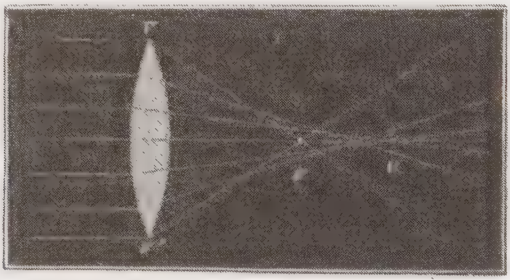


Fig. 392.

If a screen be held between the light and an ordinary double convex lens which quite covers the lens, but has two concentric series of holes, one set near the margin and the other near the centre, two images are obtained, and may be received on a sheet of paper. By closing one or the other series of holes by a flat paper ring, it can be easily ascertained which image arises from the central and which from the marginal rays. When the paper is at a small distance, the marginal rays produce the image in a point and the central ones in a ring ; the former are converged to a point and the latter not. At a somewhat greater distance the marginal rays produce a ring and the central ones a point. It is thus shown that the focus of the marginal rays is nearer the lens than that of the central rays.

Spherical aberration is greater the greater the aperture of a

lens, and the greater its curvature—that is, the smaller the radii of curvature of its faces, and therewith the focal length.

Spherical aberration is prejudicial to the sharpness and definition of an image, especially near the edges. If a ground-glass screen be placed exactly in the focus of a lens, as in a camera obscura (401), the image of an object will be sharply defined in the centre, but indistinct at the edges ; and, *vice versâ*, if the image is sharp at the edges, it will be indistinct in the centre. This defect is very objectionable, more especially in lenses used for photography.

By suitably choosing the curvatures of the faces, especially when a system of lenses is used, this defect can be greatly remedied. It is also obviated by intercepting the rays which traverse the lens near the edge by *diaphragms* or *stops*, which are opaque screens perforated by circular holes, and which only allow the central rays to pass. The image thereby becomes sharper and more distinct, though the illumination is less.

A combination of lenses by which spherical aberration is got rid of is called an *aplanatic* system of lenses.

In consequence of their greater refractive power (352), lenses of precious stones require a smaller curvature of the surfaces for the same focus, and have, therefore, smaller spherical aberration ; yet, from the difficulty of cutting them, and the great expense, they are but little used.

By using fluorspar instead of crown glass Abbe has constructed lenses in which chromatic as well as spherical aberration is still further diminished ; these are called *apochromatic* lenses.

CHAPTER VII

OPTICAL INSTRUMENTS

388. **Different kinds of optical instruments.**—By the term *optical instrument* is meant any combination of lenses, or of lenses, prisms, and mirrors. By means of optical instruments the limits of vision have been enormously increased, and the most favourable influence has been exerted on the progress of science by opening out new worlds to investigation which would otherwise have remained unknown. Optical instruments may be divided into three classes, according to the ends they are intended to answer—viz. : i. *Microscopes*, which are designed to obtain a magnified image of any object whose real dimensions are too small to admit of its being seen distinctly by the naked eye. ii. *Telescopes*, by which very distant objects, whether celestial or terrestrial, may be observed. iii. *Instruments* for projecting on a screen a magnified or diminished image of any object, which can thereby be either depicted or be rendered visible to a crowd of spectators : such as the *camera lucida*, the *camera obscura*, *photographic apparatus*, the *magic lantern*, the *solar microscope*, the *photo-electric microscope*, etc. The two former classes yield virtual images ; the last, with the exception of the *camera lucida*, yields real images.

General composition of optical instruments.—Of the various instruments enumerated above, those of the first two groups consist essentially of two lenses ; one, called the *object-glass* or *objective*, receives the light from the object and concentrates it in a focus, where it gives a small image ; the other, called the *eyepiece* or *ocular*, acts as a magnifying-glass, is near the eye, and serves to view the image formed by the object-glass. In what are called *reflecting telescopes*, a concave mirror is used instead of an object-glass. Generally speaking, the object-glass and the eyepiece are not formed each of a single glass, but of several, in order to obtain a greater magnifying power, and to correct chromatic and

spherical aberration (387). These glasses are, moreover, mounted in long metal tubes, blackened on the inside, so as to absorb the oblique rays, which would otherwise injure the sharpness of the image. These tubes can further be slid in or out, so that the glasses may be brought to the proper distance.

389. **Galileo's telescope.**—Like some other great discoveries, that of the telescope seems to have been due to chance: for it is stated to have been made accidentally by the children of a Dutch spectacle-maker, at Middelburg, named Jansen. Looking at a vane on the top of a church spire through a convex and concave glass, the latter being nearer the eye, they were surprised to see the object magnified, and apparently almost within reach. The father repeated the experiment, and arranged the two glasses in tubes, one of which slid in the other, and thus constructed the telescope.

This telescope bears Galileo's name, for this illustrious astronomer was the first to direct it towards the heavens, and to make

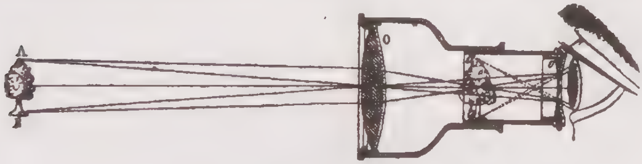


Fig. 393.

astronomical observations. It is stated that he was at Venice when he heard that Zacharia Jansen had offered to Prince Maurice of Nassau an instrument which brought objects nearer. He quickly started for Padua, where, after meditating on the matter, he made some experiments, and in twenty-four hours rediscovered the telescope.

The telescopes constructed by Galileo were gradually improved from a magnifying power of four up to one of thirty times. By their means Galileo discovered the mountains of the moon, Jupiter's satellites, and the spots on the sun.

Fig. 393 represents the arrangement of the lenses and the path of the rays in Galileo's telescope. The object-glass, O, is a double convex, while the eyepiece, *o*, is a double concave lens. If AB is the object observed, the rays from any one of its points—A, for instance—tend to form an image of this point beyond the object-

glass ; but, meeting the double concave lens, *o*, these rays appear divergent, and seem to the eye which receives them as if they proceeded from the point *a* ; and it is there the image of A appears. In like manner the image of B is formed at *b*, so that a virtual image, *ab*, is formed which is erect.

Galileo's telescope is very short and portable. It has the advantage of showing objects in their right position, and, further, as it has only two lenses, it absorbs very little light ; in consequence, however, of the divergence of the emergent rays, it has only a

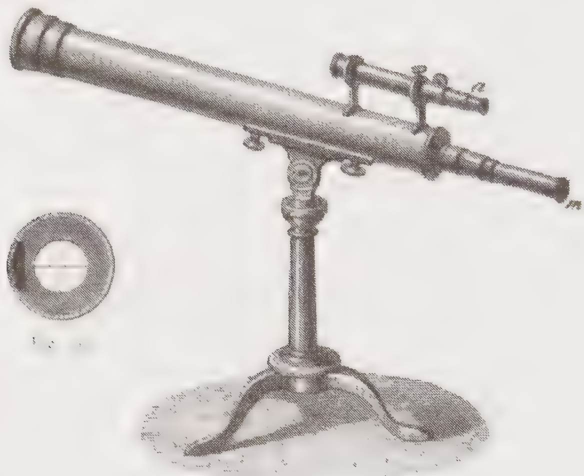


Fig. 394.

small field of view, and in using it the eye must be placed very near the eyepiece. The eyepiece can be moved to or from the object-glass, so that the image is always formed at the distance of distinct vision. *Opera-glasses* are constructed on this principle. They are usually double, so as to produce an image in each eye, by which greater brightness is attained.

390. **Astronomical telescope.**—In observing the stars a telescope with two convex lenses is used. Its invention is due to Kepler, and it is known as the *astronomical telescope.* It gives reversed images of objects, but this is not prejudicial in observing the stars.

Fig. 394 shows an astronomical telescope mounted on its stand. Above it there is a small telescope, which is called the *finder*. Telescopes with a large magnifying power are not convenient for finding a star, as they have but a small field of view; the position of the star is, accordingly, first sought by the finder, which has a much larger field of view--that is, takes in a far greater extent of the heavens; it is then viewed by means of the telescope.

Fig. 396 represents the arrangement of the lenses and the path of the rays in an astronomical telescope. It consists of two double convex lenses; the object-glass, which is of large diameter, and but slightly convergent, gives at *ab* a reversed and very small image of the object towards which the telescope is directed. This image is looked at through the eyeglass, O, which acts here as a magnifying-glass, and which, for that purpose, is placed so that the image, *ab*, is formed between it and its principal focus, F. Thus the observer sees at *dc* a reversed and enlarged image of the object.

Fig. 396.

As in all telescopes, the *eyetube*—that is, the tube in which is the eyepiece—slides in the other, so that the eyepiece can be moved nearer to or farther from the image, *ab*, which can thus be seen at the distance of distinct vision. In powerful telescopes the eyeglass is not simple, as in the above case, but consists of a number of glasses, the object of which is not only to increase the magnifying power, but also to correct spherical and chromatic aberration. There is considerable loss of light, however, when it is necessary thus to multiply the lenses.

The magnifying power of a telescope is greater the greater the diameter of the object-glass, and the less its convexity, and the more convex, on the contrary, is the eyepiece. The general rule is to *divide the focal length of the object-glass by that of the eyeglass, and the quotient is the magnifying power of the telescope.*

Increase in magnifying power by the telescope is useless beyond

certain limits, owing to the condition of the atmosphere. Only in very few cases is the air so pure and still that a magnifying power of 900 can be applied.

When the telescope is used to make an accurate observation of the stars—for example, their zenith distance, or their passage over the meridian—a *cross-wire* (fig. 396) is added. This consists of two very fine metal wires or spider threads stretched across a circular aperture in a small metal frame. The wires ought to be placed in the position where the inverted image is produced by the object-glass, and the point where the wires cross ought to be on the optic axis of the telescope, which thus becomes the *line of sight* or *collimation*.

It is very difficult to procure large masses of flint glass, free from defects and perfectly annealed, for making large object-glasses. This is one cause of the costliness of large telescope-lenses.

391. **Terrestrial telescope.**—The *terrestrial telescope* differs from the astronomical telescope in producing images in their right

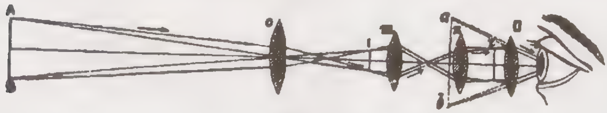


Fig. 397.

positions. This is effected by means of two convex lenses, which are interposed between the object-glass, *o*, and the eyepiece, O, as seen in fig. 397. The object-glass, forming, then, at I, a reversed image of the object, AB, the two lenses *m* and *n* impart such a direction to the rays traversing them that, after having crossed between the two lenses, the rays reproduce an erect image at *i*. The eyepiece acts then just as in the astronomical telescope, giving an erect and magnified image, *ab*.

The terrestrial telescope is sometimes mounted on a stand, and sometimes held in the hand. Its uses are too well known to need any description.

In order to determine by direct experiment the magnifying power of a telescope when this is not great, a divided scale placed at a distance, or a number of the tiles or slates of a roof, or of courses of bricks, may be viewed through the telescope with one eye and directly with the other. It is thus observed how many

unmagnified divisions correspond to a single magnified one. Thus, if two seen through the telescope appear like seven, the magnifying power is $3\frac{1}{2}$.

The excellence of a telescope depends also on the sharpness of the images. To test this, various circular and angular figures are painted in black on a white ground, as shown in fig. 398 in about $\frac{1}{10}$ the full size. When these are looked at through the telescope at a distance of 80 or 100 paces, they should appear sharply defined, perfectly black, without distortion, and without coloured edges, showing that the telescope is achromatic. Reading a book in ordinary type adjusted at a distance is also an excellent means of testing and comparing telescopes.

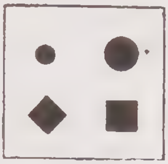


Fig. 398.

392. **Reflecting telescopes.**—The telescopes previously described are *refracting* or *dioptric* telescopes. It is, however, only in recent times that it has been possible to construct achromatic lenses of large size; before this a concave metal mirror or *speculum* was used instead of the object-glass. Telescopes of this kind are called *reflecting* or *catoptric telescopes*. The principal forms are those devised by Gregory, Newton, Herschel, and Cassegrain.

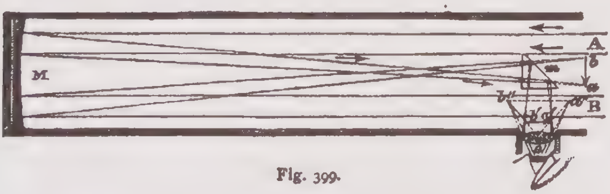


Fig. 399.

Of these we shall describe the Newtonian telescope, which, after long disuse, has been restored to favour, in great measure owing to the improvements made in the construction of the concave mirror used in it.

Fig. 399 represents the section of a Newtonian telescope. The principal piece of the telescope is a concave mirror, M, placed at the end of a long wooden tube. These mirrors were formerly of metal, and the difficulty of working them, so as to secure perfect curvature, was so great that the use of reflecting telescopes was virtually abandoned.

Foucault discovered a method of silvering glass without injuring its polish, and, glass being more easily worked than metal, reflectors for telescopes are now made of polished glass, silvered on the concave surface itself. The rays of light which come from the distant object observed are there reflected, and tend to form at *ba* a real and very small image of the object; but falling upon a small rectangular prism, *m*, which acts as a simple plane mirror (359), they form the image at *b′ a′*, and thus enable it to be examined by the lateral eyepiece, *o*.

393. **Herschel's telescope.**—Sir W. Herschel's telescope, which was long the largest instrument of modern times, was constructed on a method differing from those described. The mirror was so inclined that the image of the star was formed on the side of the telescope near the eyepiece (fig. 400); hence it is termed the *front-view* telescope. As the rays in this telescope only undergo a single reflection, the loss of light is less than in either of the preceding cases, and the image is therefore brighter. The magnifying power is the quotient of the focal length of the mirror by the focal length of the eyepiece.

Fig. 400.

Herschel's great telescope was constructed in 1789; it was 40 feet in length; the great mirror was 50 inches in diameter. The quantity of light obtained by this instrument was so great as to enable its inventor to use magnifying powers far higher than anything which had hitherto been attempted.

Herschel's telescope has been exceeded in size by one constructed by the late Earl of Rosse. This magnificent instrument has a focal length of 53 feet; the diameter of the mirror is 6 feet; and it weighs 8,400 pounds. It is at present used as a Newtonian telescope, but it can also be arranged as a front-view telescope.

The largest telescope ever constructed was exhibited at the Paris Exposition of 1900, but it has been little used. Its object-glass has a diameter of 50 inches. The diameter of the object-glass of the Yerkes telescope at the Michigan Observatory is 40

inches, and that of the large telescope in the Lick Observatory (California) 36 inches.

394. **Simple microscope.**—*Microscopes* are instruments which, giving very magnified images, enable us to observe objects which are too small to be seen with the naked eye. Two kinds are distinguished, the simple and the compound microscope.

The first of these is essentially a convex lens, which is used as a magnifying-glass, as seen in fig. 401. The object observed is placed between the lens and its principal focus, and the magnifying power is greater the more condensing is the lens. When it is rather large it is mounted in horn or in ivory, and is then known as a *reading-lens* or *reading-glass.* It is frequently used to assist the sight of the aged or to facilitate certain kinds of work which, as in watchmaking and engraving, require great accuracy. No great magnification is attainable with a single microscope, and in order to observe very small objects the *compound microscope* is used, which is so called because it is made up of several lenses.

Fig. 401.

If a drop of Canada balsam be allowed to fall on a glass plate it will assume the form of a plano-convex lens, and by holding the plate horizontally with the drop downwards it gradually becomes more convex. It soon hardens, and if protected from dust is tolerably durable. Such an arrangement forms a magnifying lens.

395. **Compound microscope.**—Fig. 402 represents a compound microscope arranged for use, and fig. 403 illustrates the path of the rays in the interior of the apparatus. The object, which is always very small, is placed between two glass plates, which can be kept in position by two spring clamps on a support called the *stage*, A. The brass tube B contains two condensing glasses, the *object-glass*, *o*, at the bottom, and the *eyepiece*, O, at the top. The object, *a* (fig. 403),

being placed very little beyond the principal focus of the lens *o*, a real inverted and greatly magnified image will be formed at *cb* (365). But as the eyepiece, O, is at such a distance that the image, *bc*, is between this glass and its principal focus, F, it follows that the eyepiece acts as an ordinary magnifying lens for an eye looking through it (367), and gives at CB a virtual and amplified

Fig. 402.

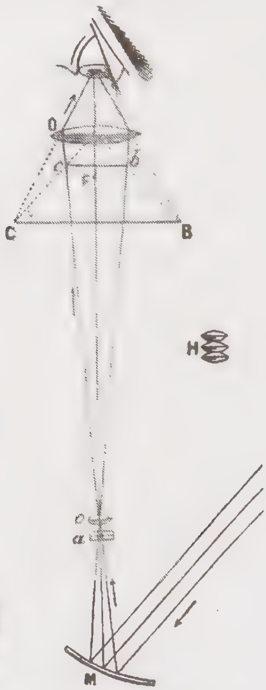


Fig. 403.

image of the first image, *cb*. It may be said that the compound microscope is nothing more than the simple microscope applied, not to the object, but to its image already magnified by the first lens.

The magnification depends more especially on the object-glass. In order to increase its power it is usual to construct the object-glass of two or three small lenses superposed, as seen in H, on the

right of the drawing (fig. 403). To the eyepiece a second glass is added, the object of which is less to obtain increased magnification than to render the images more defined by diminishing, as in telescopes, chromatic and spherical aberration. All the glasses are, moreover, achromatic. The magnifying power in compound microscopes has been carried to 1,800 times, and even more, but then what is gained in magnification is lost in definiteness. A good magnification does not exceed 600 in length and breadth; this is called a magnification of 600 diameters, which amounts to a superficial enlargement of 360,000 times.

From the great magnification of the image the object must be powerfully illuminated. For this purpose, when it is sufficiently transparent, it is illuminated from below by a concave mirror, M, which concentrates upon it a large quantity of light, as shown in fig. 403. If the object is opaque, it is illuminated from above by a condensing lens, the focus of which is formed upon the object itself.

396. **Origin and use of the microscope.**—The invention of the microscope does not extend further back than to the last quarter of the seventeenth century—which is surprising, for it had long been known that a drop of water placed in a small hole in a thin opaque plate magnified objects seen through it. From the commencement of the first century A.D. the philosopher Seneca announced that writing appeared larger under a glass globe containing water. In the thirteenth century *spectacles* were first used —that is, magnifying-glasses—to assist the sight of the aged. They are said to have been discovered by Salvino degli Armati, a Florentine nobleman. The inventor of the microscope is not known; it has, probably, only acquired its present form after numerous successive improvements.

The microscope has been the origin of discoveries in the vegetable and animal kingdoms as curious and important as they are varied. Botanists owe to it their most beautiful discoveries concerning the structure of the cellular tissue in plants, the circulation of the sap, the function of leaves in the respiration of vegetables. In entomology it has enabled us to discover a crowd of small animals which would otherwise have remained unknown from their extreme minuteness. Thus there have been observed in vinegar and in sour paste thousands of small organisms called bacteria; in stagnant water myriads of animalcules, as remarkable for their curious forms as for their beautiful colours, their instincts,

their warlike or sociable habits. Mildew presents the appearance of small mushrooms with the most brilliant colours. In short, any object seen through the microscope becomes an object of astonishment and admiration; thus, for instance, a hair, a piece of silk thread, the eye or wing of a fly, a bee's sting, a spider's claw, a cat's or a mouse's hair, the down of fruit, the scales of a butterfly's wing or of fish, starch grains, spider's web, etc.—everywhere we recognise the infinite variety of Nature's works.

The simple microscope may be also advantageously used to detect fraudulent mixtures in cloths of various kinds, by giving a means of ascertaining whether they contain wool or silk, linen or cotton. By the watchmaker it is used to inspect the minute mechanisms with which he has to deal.

The excellence of a microscope depends not so much on the mere magnifying power as on the sharpness, or what is called the *definition*, of the images. It is tested by means of what are called *test objects*, such as particular specimens of a butterfly's wings or scales of certain diatoms; or by means of fine lines drawn on glass. Such lines have been drawn of which there are no less than 10,000 in an inch.

CHAPTER VIII

OPTICAL RECREATIONS

397. **Magic lantern.**—In the instruments that still remain to be described the aim is to project on a screen reduced or enlarged images of an object, so as to exhibit them to a number of spectators, or to utilise them for drawing.

The oldest and most simple of these apparatus is the *magic lantern*, which was invented by Father Kircher, a German Jesuit, about two hundred years ago, and is used to project a magnified image of small objects painted on glass on a white screen in a

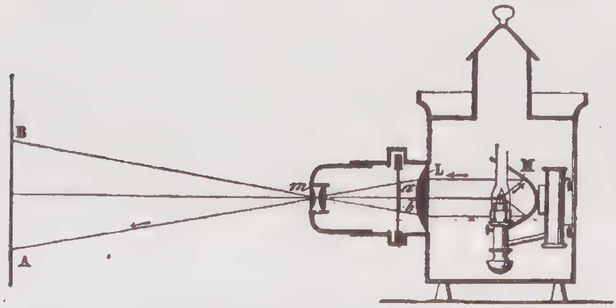


Fig. 404.

dark room. It consists of a box of sheet metal, in which there is a lamp placed in the focus of a concave mirror, M (fig. 404). The reflected rays fall upon a condensing lens, L, which concentrates them on a glass plate or *slide*, *ab*, on which is photographed or painted the figure to be reproduced. There is a system of two lenses, *m*, acting as a single one of great magnifying power, at a distance from *ab* of rather more than its focal length. At this distance the system of two lenses acts as the object-glass of a

microscope (fig. 403)—that is, a real and very much magnified image of the figure on the slide is produced on the screen. The image is made erect by placing the slide in the lantern in such a manner that the design is reversed. The image, AB, is formed at so much the greater distance, and is so much the more amplified, the nearer the slide, *ab*, is to the principal focus of the system of lenses, *m*, and the greater the magnification of this system.

398. **Phantasmagoria.**—This is only a modification of the magic lantern, and dates from the end of the eighteenth century; its name is derived from two Greek words which signify *assemblage of phantoms*, for it was originally used to produce fright by making spectres appear in darkness.

Fig. 405.

The internal arrangement of the phantasmagoria is just the same as in the magic lantern, the difference being that in the magic lantern the image projected on the screen is always of the same size, while in the case of the phantasmagoria the size may be varied at pleasure. To understand how this is effected, let us refer to fig. 404, which represents the arrangement of the glasses in the magic lantern. The lenses, *m*, which are used to project the images on the screen, being always at the same distance from the painted slide, *ab*, the image, AB, is always at the same distance, and is always, therefore, of the same size. Now, if the lenses, *m*, be brought nearer the slide, *ab*, it follows from the properties of

lenses (367) that the image will be formed at a greater distance, and will be larger. Hence the effect sought requires two movements—one which brings the system of lenses, *m*, nearer the painted slide, to amplify the image; the other, which makes the whole apparatus recede, so that the image, while being moved away, is always formed upon the same screen as at first.

To obtain this double effect the whole apparatus is mounted upon four small wooden wheels covered with cloth, so that they roll noiselessly on the floor. Fig. 405 represents a phantasmagoria thus arranged, with the difference that in the figure it is double—that is, consists of two apparatus united. We shall presently see the reason for this double use (399), but for the moment we shall only consider one of the parts. The front of the box is provided with a conical brass tube; in this tube is the projection lens, which is not fixed, but may be advanced or moved back by means of a milled head and screw, which the experimenter turns with the hand.

A large white sheet is stretched in front of the apparatus, and the spectators are on the other side of the sheet, the whole being in complete darkness. The experimenter is careful first of all to keep the projection lens away from the slide, on which are painted the objects he desires to show. Thus there is at first formed on the sheet a very small image of the object. Then, with one hand, the experimenter brings the lens near the slide, while with the other he draws the apparatus towards himself, and away from the cloth. The image projected on the latter gradually increases, and ultimately becomes very large. The spectators, who see the image very distinctly through the cloth, fall into the illusion that its increase in size is due to its coming nearer them.

399. **Dissolving views.**—These are produced by a double lantern, as represented in fig. 405, with two systems of lenses which converge towards the same point of the cloth which receives the image. Two pictures on glass are used, representing the same view under different conditions—for example, Mount Vesuvius seen at daytime, calm, and with a slight cloud of smoke rising from it; the other when seen at night, vomiting forth flames and torrents of fiery lava. Having arranged these glasses, each in one of the lanterns, and the lenses being so adjusted as to project the magnified images on exactly the same part of the cloth, the diaphragm of the one containing the picture representing the effect of day is opened, the other remaining closed. Then, when the image has

for some time been exposed to the view of the spectators, a mechanism is worked which gradually closes the one which has been exposed, and opens the other. It follows that, in successively passing through all the shades of light, the image which produces the effect of day disappears, while it is gradually replaced by the effect of night represented on the other. In like manner, too, the effect of the moon rising may be made to succeed to sunset; to a calm and transparent sea, a tempest; to a smiling landscape, a snow effect; and so forth.

400. **Photo-electric microscope.**—This apparatus is based on the same principles as the magic lantern and the phantasmagoria.

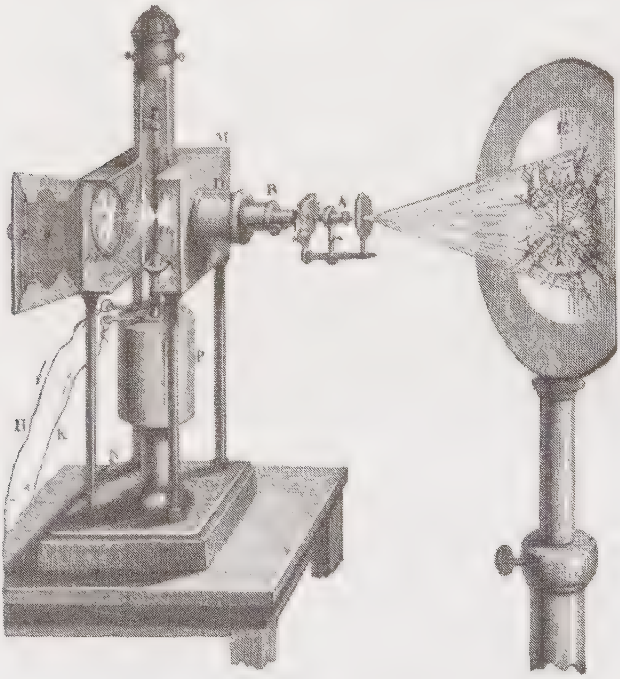


Fig. 406.

But as in these apparatus the subjects painted on glass are of some size, no great enlargement is required, and therefore the illu-

mination need not be very bright; whereas objects the images of which are reproduced by the photo-electric microscope, being very small, should be considerably magnified, and the light must therefore be very powerful, or else the image will be confused and indistinct. Hence the apparatus is illuminated by the powerful light which electricity yields.

Fig. 406 represents the use of the photo-electric microscope. The brilliant light of the electric arc, *ca*, produced by either a powerful voltaic battery or a dynamo-electric machine, is reflected from the mirror, *m*, and passes through condensing lenses at D and B, the function of which is to condense the light upon the small object to be magnified, which is placed between two glass clips, between B and A. The projecting lenses are in the little tube A, and the object must be just beyond their principal focus. Under these circumstances a brilliant and greatly magnified image is formed on a white screen at a distance. P contains an electro-magnetic arrangement, to be described in its proper place, for keeping the carbon points at a constant distance apart, which is essential for the steadiness of the light.

401. **Camera obscura.**—A Neapolitan physicist, Giambattista della Porta, first observed, in 1569, that if a very small hole be made

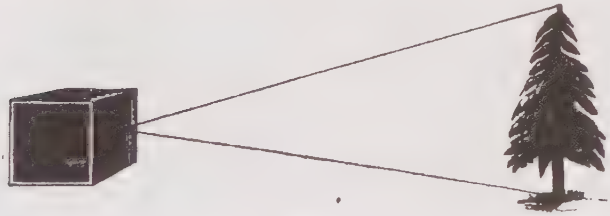


Fig. 407.

in the shutter of a *dark room*—one that is quite deprived of light—all objects from which rays can reach the hole depict themselves on the opposite screen, and of so much the smaller dimensions the nearer this screen is to the aperture.

Porta also found that by fixing a double convex lens in the aperture, and placing a white screen in the focus, the image was much brighter and more definite. In both cases the images are inverted. Fig. 407 shows how images formed in the camera obscura are reversed upon the screen. It is due to the rays crossing on

entering the aperture. It follows, in fact, that rays from the higher parts of the object, proceeding in straight lines, meet the lower part of the screen, while the reverse is the case with rays from the lower part. The coloration of the image is readily understood by observing that the reflected rays are of the same colour as the reflecting body—that is, that a red body reflects red rays, a yellow body yellow rays, and so on. Each portion of the image is formed by the coincidence of rays of the same colour as the corresponding part of the object it represents.

Fig. 408.

The images formed in the camera obscura have the peculiarity of being independent of the shape of the aperture through which the rays enter, *provided this is very small*—that is, that, whether this aperature is round, square, or triangular, the image formed on the screen is always a faithful reproduction of external objects, and not of the hole made in the shutter. To account for this phenomenon, let us consider the case of a pencil of sunlight of any shape whatever passing into a dark room (fig. 408). Compared with the magnitude of the sun, this hole is really nothing more than a point ; whence it

follows that the whole of the rays which traverse it represent an immense luminous cone, of which the hole is the summit and the sun the base. By their being prolonged into the chamber these rays give rise to a second cone resembling the first, but far smaller; and if this second cone falls upon a screen which is perpendicular to the straight line joining its summit to the centre of the sun, it produces on this screen a circular image like the sun. If the screen is obliquely inclined towards this line, as represented in fig. 408, the image is elliptic, but it never has the shape of the aperture unless the screen is very close.

In the same manner we must explain the luminous patches formed on the ground under an avenue of trees illuminated by the sun. Whatever be the shape of the spaces in the foliage through which the light passes, a circular or oval image of the sun is projected upon the ground.

402. **Photography.**—*Photography* is the art of fixing the images of the camera obscura on substances *sensitive* to light.

Wedgwood was the first to suggest the use of chloride of silver in receiving the image; and Davy, by means of the solar microscope, obtained images of small objects on paper impregnated with chloride of silver; but no method was known of preserving the images thus obtained, by preventing the further action of light. Niepce, in 1814, obtained permanent images in the camera by coating glass plates with a layer of varnish composed of bitumen dissolved in oil of lavender. This process was tedious and inefficient, and it was not until 1839 that the problem was solved. In that year Daguerre described a method of *fixing* the images of the camera, which, with the subsequent improvements of Talbot, Archer, and others, has rendered the art of photography one of the most marvellous discoveries ever made, whether as to the beauty and perfection of the results, or as to the celerity with which they are produced.

Fig. 409 gives a vertical section of one kind of camera obscura used by photographers. It consists of a rectangular wooden box in two pieces, one of which, C, is fixed, and the other, B, can be pushed in or out like a drawer. In the front of the box C is a brass tube, A, in which is a condensing lens, L, which is fixed. In A is a second tube, which can be moved backwards or forwards by a rack and pinion moved by the milled head D. In this second tube is a second lens, L′, which, by the motion of the tube, is brought nearer to or further from the lens L. The advantage of this combination of lenses is, that it works more rapidly than an object-glass with a

single lens, has a shorter focal distance, and can be more readily focused.

On the face of the box opposite the object-glass is a screen of ground glass, E, which can be moved backwards or forwards at will, and fixed in any position by means of the screw *n*, and on which a reversed image of the object is formed. Thus, if a portrait is to be taken, the person is placed at a distance of three or four yards from the camera, which is then adjusted until the image is formed in the proper position on the glass. It is next placed in exact focus by slowly approaching or removing the lens L′. The glass is contained in a frame which can be easily removed and replaced by the slide containing the material on which the photograph is to be taken.

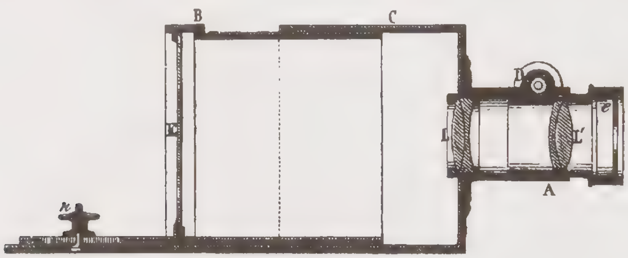


Fig. 409.

The photographs on metal, or *daguerreotypes*, so called from Daguerre, the inventor, are now seldom used. The photographic methods in glass and paper are infinitely varied, not as regards the essential features of the optical part, but as concerns the substances employed, and therefore as regards the chemical reactions involved.

We will content ourselves with describing the ordinary method of taking a portrait on paper. For this purpose what is called a *negative* must first be taken—an inverse image of the object, that is to say, in which the light parts are dark, and *vice versâ*. With this view a glass plate is coated with a thin layer of *collodion* (gun-cotton dissolved in ether) containing a certain quantity of potassium iodide. The plate thus coated is then placed in a solution of silver nitrate. By the chemical reaction between the potassium iodide and the silver nitrate a coating of silver iodide is formed on

the plate, which is sensitive to light, and hence this operation must be performed in a dark room. The plate is then placed in the slide, and inserted in the camera instead of the focusing-glass. The slide is so constructed that the plate can be instantaneously exposed to or cut off from the action of light. After exposure for a suitable time the slide is removed to a dark room. No change is visible in the plate, but on pouring over it a solution called the *developer* an image gradually appears. The principal substances used for developing are iron sulphate and pyrogallic acid. The action of light on silver iodide produces some change, in virtue of which the developers have the property of reducing to the metallic state those parts of the silver iodide which have been most acted upon by the light. When the picture is sufficiently brought out, water is poured over the plate, in order to prevent the further action of the developer. The parts on which light has not acted are still covered with silver iodide, which would also be affected if the plate were now exposed to the light. It is accordingly washed with solution of sodium hyposulphite, which dissolves the iodide of silver and leaves the image unaltered. The picture is then washed, dried, and coated with a thin layer of spirit-varnish to protect it from mechanical injury.

When once the negative is obtained, it may be used for printing an indefinite number of positive pictures. For this purpose, paper is impregnated with silver chloride, by floating it first on a solution of sodium chloride, and then, when dry, on one of nitrate of silver; silver chloride is thus formed on a paper by double decomposition. The negative is placed on a sheet of this paper in a copying-frame, and exposed to the action of light for a certain time. The silver chloride becomes acted upon—the light parts of the negative being most affected, and the dark parts least so. A copy is thus obtained in which the lights of the negative are replaced by shades, and conversely. The picture is next immersed in a bath of gold chloride, by which those parts on which the light has acted become coated with gold; and, according to the extent to which the process is carried, different shades of colour are produced. The picture still contains some unaltered silver chloride, which would be changed if it were now exposed to the action of light; and to *fix* it the picture is immersed in a solution of sodium hyposulphite, which dissolves the unaltered silver chloride. Finally the picture is well washed with pure water, which dissolves out the sodium hyposulphite and all other soluble salts.

Of late years permanent and very beautiful prints have been obtained from negatives by making use of the chemical change produced by light on a mixture of potassium bichromate and gelatine. On this reaction are based the various carbon processes, and those for mechanical printing. Very beautiful prints, with an effect resembling that of steel engravings, are produced by what is known as the *platinum process*. This consists in exposing paper charged with ferric oxalate to the light, and then developing the prints thus produced by a platinum salt; the ferric salt by exposure to light is reduced to ferrous oxalate, which in turn reduces the platinum salt to black metallic platinum.

403. **Positives on glass.**—Very beautiful positives are obtained by preparing the plates as in the preceding cases; the exposure in the camera, however, is not nearly so long as for the negatives. The picture is then developed by pouring over it a solution of iron protosulphate, which produces a negative image; and by afterwards pouring a solution of potassium cyanide over the plate this negative is rapidly converted into a positive. It is then washed and dried, and a coating of varnish poured over the picture.

404. **Photographic dry plates.**—The possibilities of photography have been greatly increased by the rapid development of what are known as *dry plates*. These are made from an emulsion consisting essentially of gelatine, with which are incorporated bromide and other sensitive salts of silver. Glass plates are coated with emulsion, and are then dried. By varying the composition of the mixture, and by care in manipulation, plates may be obtained which not only produce pictures of great beauty, but require only a very small fraction of a second for their exposure. Such plates may, indeed, be said to be almost instantaneous; it is possible by the most sensitive of them to photograph an express train moving at a rate of 100 feet a second, and even lightning flashes, the duration of which does not probably exceed the $\frac{1}{100000}$ of a second. Plates of this kind will keep for months, and even years, and, provided light is carefully excluded, may be kept after exposure for a long time before development. These advantages, together with the improvements in the portability of cameras, are of especial importance and value to travellers.

405. **Ghost-scenes.**—We will give here a description of a curious optical effect, which was first introduced some years ago in the theatres under the name of *ghost-scenes*.

In order the more readily to understand the appearance of these spectres, let us recall an effect which every one has observed. When on a railway journey, towards evening, we look at the windows of carriage doors, we see a pale and indistinct image of the travellers inside. This is an effect of reflection from the panes, which reflect the light that illuminates persons and objects placed in the compartment; and the faint light of the images arises from the fact that the panes, allowing great part of the light to be transmitted, send very little towards the observer. A similar effect is produced when, in the evening, in a well-lighted street, a window-front which is little or not at all lighted is looked at. The observer sees on the other side of the panes his own image and those of other people in the street. These effects are not seen in full daylight, for the images which are produced are effaced by the brightness of the light which comes through the glass.

These phenomena have been utilised in public to simulate the appearance of ghosts. Fig. 410 represents the arrangements of the apparatus intended for this purpose. On the floor below the stage, and not seen by the spectators, is an actor, covered by a sheet, and intended to represent the ghost. Between the actor and the public is a magic lantern, illuminated by limelight or by the electric light, so as to give an extremely bright illumination. An assistant directs the light upon the actor, and the white cloth, thus powerfully illuminated, sends its rays towards an inclined plate of glass, placed near the assistant. This glass, which is silvered, sends almost all the reflected light towards a second plate, which is not silvered, on the same scene. This latter plate acts like those in carriages and in shop-windows, which we have mentioned above, and, being traversed by the greater part of the incident rays, sends but little light towards the spectators. Yet, as care is taken during this time that the illumination in the room is very faint, the light is sufficient to give a shadowy image of the actor placed under the stage.

If another actor enters the scene, the public see very distinctly through the glass, which is carefully concealed by hangings and decorations; and if this actor is behind the plate at the same distance as the image, he can join his action with that of the ghost, and thus produce a complete illusion.

The same effects are produced with a single plate, but, as its obliquity tends to give inclined images, in order to rectify them the actor under the stage must hold himself so much inclined as to

render his play very difficult. With the two plates represented in fig. 410 the actor retains his natural position.

Fig. 410.

406. **Structure of the eye and mechanism of vision.**—The shape of the eye is approximately a sphere. It is enveloped by a white coat—the *sclerotic coat*, commonly called the white of the eye—which is opaque, except in front, where it is transparent and slightly more convex than the rest of the eyeball. This transparent portion is called the *cornea*, *a*. At a small distance behind the cornea is a membranous diaphragm, *d*, called the *iris*; it constitutes the variously coloured disc which is seen through the cornea, and to which is due the colour of the eye. In the centre of the iris is an aperture called the *pupil*; in man this is circular, and in the cat narrow and elongated, and through it rays pass into the eye. Behind the iris, but very near it, is the *crystalline lens*, *j*, which is a transparent mass, having the shape and fulfilling the functions of a double convex lens. The whole of the hinder part, from the crystalline lens to the back of the eye, is filled with a gelatinous transparent mass, like white of egg, which is called the *vitreous humour*. In front of the eye, between the crystalline lens and the cornea, is a perfectly transparent liquid, called the *aqueous humour*. The whole of the back inside part of the eye is lined with a soft whitish transparent membrane, *l*, called the *retina*; in it are the extensions of the bundle of nerve fibres, *n*, which proceed to the brain, and transmit the sensation of vision, whence the bundle receives the name *optic nerve*. Behind the retina is a second membrane, *k*, called the *choroid*, which is impregnated by a black matter that absorbs all rays which should not co-operate in producing vision. Lastly, a membrane, *i*, the *sclerotic*, surrounds the whole eyeball behind, and joins the transparent cornea in front. It forms in front a series of projecting folds, which are called ciliary processes.

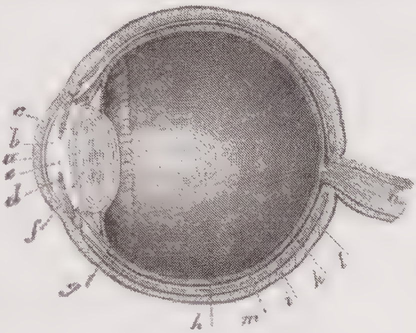


Fig. 411.

These details being known, we may readily account for the mechanism of vision; for the eye is, in fact, a small camera obscura

(401), of which the pupil is the aperture, the crystalline is the condensing lens, and the retina is the screen on which the image is formed. The optic nerve, carrying thence to the brain the impression produced by the vibrations of the luminiferous ether on the nervous system of the retina, enables us to perceive external objects. In accordance with this explanation we should see objects reversed, and not in their natural position. The inversion of images in the eye has greatly occupied both physicists and physiologists, and many theories have been proposed to explain how it is that we do not see inverted images of objects. Some have supposed that it is by custom, and by a regular education of the eye from early infancy, that we see objects in their true position—that is to say, in their position relative to us : the visual impression becomes corrected by the impression of other senses, such as that of touch. Müller, Volkmann, and others have contended that, as we see everything inverted, and not simply one object among others, nothing can appear inverted, because terms of comparison are wanting. The chief difficulty seems to have arisen from the conception of the mind or brain as something behind the eye, looking into it, and seeing the image upon the retina : whereas, really, this image simply causes a stimulation of the optic nerve, which produces some molecular change in some part of the brain, and it is only of this change, and not of the image as such, that we have any consciousness.

If the eye is exposed to too powerful a light, the *pupil* contracts and only a smaller quantity of rays are admitted and strike the retina ; in a dimmer light the exact reverse is the case. This increase or decrease is limited, however, and in too strong or too dim a light objects cannot be distinctly seen. If the eye has for some time been exposed to a bright light, it becomes insensible to feebler ones. On coming suddenly into a dark room we cannot distinguish objects which after a while can be distinctly seen. After the retina has, as it were, recovered from the too strong stimulus, its sensitiveness to feebler impressions gradually increases.

407. **Distance of distinct vision. Accommodation. Short and long sight.**—We know that in double convex lenses the distance of images from the lens increases or diminishes as the object is approached or receded from (361–363). Hence, according to the distance of the objects looked at, it would seem that the image formed by the crystalline should be sometimes formed exactly on

the retina, and sometimes a little in front of or behind this membrane. Only objects placed at a certain distance should then be seen distinctly; all those nearer or further should appear confused.

Experience shows us, however, that the eye can see distinct images of objects at very different distances. We can, for example, see a distant tree through a window, and also a scratch on the pane, though not both distinctly at the same moment; for when the eye is arranged to see one clearly, the image of the other does not fall accurately upon the retina. An eye completely at rest seems adapted for seeing distant objects; the sense of effort is greater when a near object is looked at after a distant one than in the reverse case.

The power which the eye possesses of voluntarily adapting itself, so that it can form distinct images on the retina of objects at very different distances, is called its power of *accommodation*.

When the eye is adjusted for a near object, the entire crystalline lens is pushed forward by means of pressure exerted by the muscles of the eye, and the front surface is made more convex; when the eye has been adjusted for a distance, and then the pressure is relaxed, the lens becomes flatter; the rays are then less strongly refracted, and the image recedes a little.

Yet, though the eye can well distinguish objects at very different distances, there is, in the case of each person, a distance at which objects are more distinctly seen than at any other. This distance is called *the least distance of distinct vision*; it varies with different persons, and often in different eyes in the same individual; for small objects like print it is usually 10 or 12 inches.

In order to obtain an approximate measurement of the least distance of distinct vision, two small parallel slits are made in a card at a distance of 0·03 of an inch. These apertures are held close before the eye, and when a fine slit in another card is held very near them, the slit is seen double, because the rays of light which have traversed both apertures do not intersect each other on the retina, but behind it. But if the latter card is gradually removed, the distance is ultimately reached at which both images coincide and form one distinct image. This is the distance of distinct vision. Stampfer constructed an *optometer* on the principle of this experiment, which is known as *Scheiner's experiment*. The least distance of distinct vision may also be determined by looking along a tightly stretched thread and observing at what distance it

ceases to appear as a line, and widens into a band owing to its not being seen sharply.

Those who can only see well at shorter distances have a defect in the shape of the eye; they are said to be ***myopic***, or ***short-sighted***, from two Greek words which signify *to close the eyes*; for myopic persons, in order to see more distinctly, do in fact involuntarily half close the eyes. If the least distance of distinct vision is greater than 10 or 12 inches, that is also due to a malformation of the eye, and those affected by it are called ***presbyopic***, or ***long-sighted***, from a Greek word which signifies *aged*, for this defect is usually met with in aged persons.

Myopy, or short sight, results from too great a convexity of the crystalline lens. The eye being too convergent, the rays of light from an object—M, for instance—are refracted in such a manner that, instead of forming their focus exactly on the retina, they form

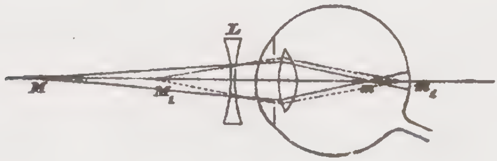


Fig. 412.

it a little in front, at *m* (fig. 412), and therefore the image is confused. But if objects are brought nearer to the eye, as at M_1, the image recedes, and is formed exactly on the retina, m_1, when the objects are sufficiently near, which explains why short-sighted persons only see objects when they are very close. Myopy is mainly met with in young people; as they grow older the convexity of the crystalline lens diminishes, so that their sight generally becomes better when that of other people becomes worse.

Presbyopy, or long sight, is due to the flattening of the crystalline; as the eye is then no longer sufficiently convergent, the rays from M (fig. 413), instead of forming their focus on the retina, tend to form it beyond at *m*, whence it arises that the eye only observes a confused image. But, as the object recedes as at M_1, the image comes nearer the crystalline, and is ultimately formed exactly on the retina, when objects are sufficiently distant; this is the reason

why long-sighted persons see objects most distinctly when they are distant.

Short sight is remedied by the use of concave or diverging lenses before the eyes (L, fig. 412); as the pencil is spread out before entering the eye, the rays appear to reach the eye from a point, M_1, nearer than M. That is, the interposition of the concave lens has the effect of bringing the object nearer to the eye. For far sight, on the contrary, condensing or convex lenses should be used (L, fig. 413), so as to correct the want of convexity of the crystalline. As the rays then become more convergent before

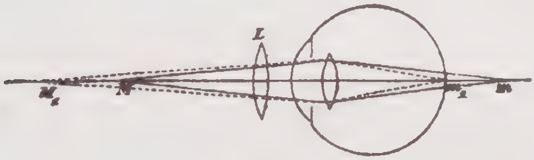


Fig. 413.

entering the eye, the image, which would otherwise be formed beyond the retina at *m*, approaches it, and is ultimately formed exactly upon it at m_1.

For a long time double concave lenses were exclusively used for short sight, and double convex for far sight. The concavo-convex lenses represented in O (fig. 360) are recommended for long sight, and those in R (fig. 361) for short sight. These are called *periscopic glasses*, from two Greek words meaning *to see round*; for as their shape better enables them to embrace the eyeball, they facilitate vision in all directions; and as they do not deform objects, they do not fatigue the eye like other glasses.

408. **Binocular vision.**—Although we have two eyes, and when we fix them on the same object each forms its own image upon the retina, yet we see only one object, just as with two ears we hear only one sound. Various hypotheses have been made to account for single vision with two eyes. Some have considered it as an effect of habit; others, assigning to it a physiological cause, have assumed that two points similarly placed on the two retinas correspond to the same nervous filament which, coming from the brain, bifurcates towards each eye. Hence the two impressions simultaneously produced on the two retinas result in a single sensation

Not only does simultaneous vision with two eyes enable us to see bodies with greater lustre, but the imperfections of one eye are corrected by those of the other ; it also gives us the impression of relief, as the stereoscope well shows, and it is a most important aid in estimating the distance and magnitude of objects.

409. **Stereoscope.**—The *stereoscope*, so called from two Greek words which mean *perception of solidity*, is an ingenious instrument, which was invented by Sir C. Wheatstone, and modified to its present form by Sir D. Brewster.

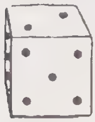


Fig. 414.

Fig. 415.

To understand the effect of the stereoscope, let us observe that when we look at an object with two eyes, each eye does not see it under exactly the same aspect, but under a slightly different perspective. Thus, let a small object, such as a die, be successively viewed with one eye, at a slight distance, without moving the head. If the cube be just in front of the observer, looking at it with his left eye, he will see the face and a small portion of the left side, the other being concealed (fig. 414) ; if, on the contrary, he views it with his right eye, he sees the front and a portion of the right side, the other being hidden (fig. 415). Thus the two images formed on the retina are not quite identical, for each corresponds to a different point of view. It is this difference in the images which gives us the sensation of relief in bodies, and enables us to appreciate their shape and their distance.

This may be confirmed by making two drawings of the same object, taken respectively with the perspective belonging to the right and to the left eye ; then, as each eye looks separately at the drawing through prisms or lenses, which make the two drawings coincide, by giving the rays of light the same direction as if they converged from a single object, the impressions produced upon each retina will be the same as if the object itself were viewed. The illusion is in fact so complete that, however prejudiced we may be, it is impossible not to be deceived, so true are the effects of relief and perspective.

This is the principle of the stereoscope. Fig. 416 shows the path of the rays of light in the instrument. At A is the drawing of the object seen with the left eye ; at B that of the same object seen with the right. The rays from these images fall on two half-lenses, *m* and *n*, and take, after having traversed them, the

same direction as if they came from the point C; the object represented at A and B appears in relief at this spot.

The lenses *m* and *n* must impart exactly the same deviation to the rays, and they should therefore be exactly identical. Brewster attained this result by cutting in halves a double convex lens, and placing the right half in front of the left eye and the left half in front of the right eye, as shown in fig. 416.

Fig. 416.

To produce the sensation of relief, the two dissimilar pictures at A and B should give from two different points of view so faithful a representation of the same object that these separate views cannot be taken by hand drawing; it is only practicable by means of photography. Fig. 417 represents two photographs of Sir C. Wheatstone taken at a slightly different angle. That on the left represents more of the full face, and must be looked at with the left eye; the other one is more in profile, and must be viewed with the right eye. These two views being placed

Fig. 417.

in the stereoscope disappear as such, and their images, seen by each eye, coalesce, and form a single image, as represented in

fig. 418, and the original appears so solid, with such perfect relief, that the imagination can with difficulty realise the fact that we are only concerned with drawings on a plane surface.

Two photographs of the moon taken from different positions on the earth, and placed in the stereoscope, are extremely interesting; the plains, mountains, and valleys on the moon's surface stand out with great vividness.

If the position of the pictures be reversed—that is, if the right-hand picture is viewed with the left eye, and *vice versâ*—the elevations of the pictures appear as depressions, and the depressions as elevations; thus the image produced is that of an *intaglio*. Such pictures are called *pseudoscopes* (ψευδής, false).

Fig. 418.

When the two eyes view simultaneously two different colours, the impression produced is that of a single mixed tint. The power, however, of combining the two tints into a single one varies in different individuals, and in some is extremely weak. If two white discs be placed in the stereoscope and be illuminated by two pencils of complementary colours, a single white disc is seen, showing that the sensation of white light may arise from two complementary and simultaneous chromatic impressions on each of the two retinas.

If two pictures are absolutely identical, they form a perfectly flat picture in the stereoscope. If, however, there are minute differences, the eyes make movements in order to combine the two

images, and there is formed a stereoscopic picture. This process has been used to distinguish between forged and genuine bank-notes, between two different editions of the same printed work, and the like.

That binocular vision is of great service in the exact appreciation of distance is seen from the difficulty we experience in threading a needle when one eye is closed.

Another illustration of this is the following: a thin metal ring about 2 inches in diameter, is suspended by a thread, and in a rod about 2 feet in length is fitted a stout iron wire bent at right angles. It will now be found almost impossible to put the end of the wire in the ring if either eye is closed, but this is most easily effected when both eyes are open.

BOOK VII

ON MAGNETISM

CHAPTER I

PROPERTIES OF MAGNETS

410. **Natural and artificial magnets.**—Natural magnet, or *lodestone*, is a mineral which has the property of attracting iron and a few other metals, especially nickel and cobalt. This mineral is an oxide of iron—that is, a compound of iron and oxygen. When a piece of lodestone is dipped into iron filings, the filings are attracted by and cling to the lodestone (fig. 419), chiefly at opposite ends or edges.

Fig. 419.

Lodestone has another property, which is not less remarkable—namely, that when it is placed in a stirrup, suspended to a thread or placed on a cork which floats on water, it constantly points towards a certain direction of the horizon.

This lodestone, or magnetic stone, was known to the ancients, who called it Lydian stone, or Magnesian stone ; for it was first found near a village called Magnesia, in Lydia. And from this place the Greeks derived the name *magnes*, from which is obtained the word magnetism, under which name philosophers understand the whole of the properties which magnets possess. Magnetic iron ore is very abundant in Nature : it is met with in the older geological formations, especially in Sweden and Norway, where it is worked as an iron ore, and furnishes the best quality of iron.

Artificial magnets are usually made of steel. When steel is hardened by being raised to a high temperature, and suddenly cooled by immersion in cold water, it acquires great hardness and

may be converted into an artificial magnet. The magnetic property may be imparted to it by rubbing it with a powerful magnet, either natural or artificial; and it then becomes itself a permanent magnet.

Artificial magnets have just the same properties as natural magnets, but are far more powerful and convenient; they are, accordingly, almost universally used in experiments. They are sometimes made into bars a foot or two long, like that represented in fig. 420; sometimes in a horseshoe form (fig. 440); or, lastly, if they are to be free to move, they are cut out of a thin sheet of steel in the shape of a lozenge, as shown in fig. 422. A small agate cup is let into the centre, in such a manner that the needle can rest on a vertical pivot and oscillate freely in a horizontal plane. Thus arranged the artificial magnet becomes a *magnetic needle* or a *compass needle*.

Fig. 420.

411. **Distribution of magnetism in magnets.**—The force with which a magnet attracts iron is not the same at all parts of it. The greatest attraction is at the ends; it decreases rapidly from there towards the middle, where there is no attraction. For, if a magnetised bar is immersed in iron filings, when it is withdrawn the filings are seen to adhere to the ends in long and compact filaments (fig. 420), but not a particle adheres to the middle.

The two parts near the ends where the attraction is most powerful are called the *poles* of the magnet, and the medial part where there is no attraction is called the *neutral line*. All magnets, natural or artificial, have each two poles and a neutral line. A single magnetic pole cannot exist by itself. Sometimes, besides the two principal poles, there are observed intermediate poles, which are called *consequent poles*. These arise from some inequality in the temper of the steel, or from the manner in which the bar has been magnetised. We shall always assume that magnets, being properly magnetised, have only two poles.

The action of magnets upon iron is exerted through all bodies

which are not themselves magnetic. Thus, a magnet being placed on a table and a piece of cardboard rested upon it, iron filings are allowed to fall through a sieve (fig. 421). The filings fall while the cardboard is tapped, and being acted upon by the two poles they become arranged in long filaments, which group themselves along

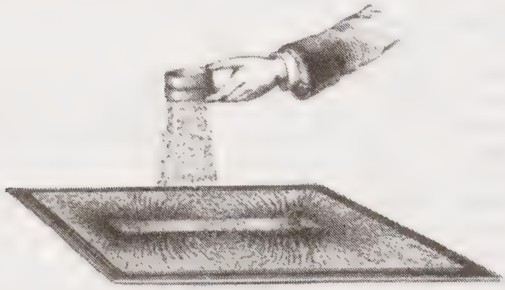


Fig. 421.

curved lines from one end of the magnet to the other; but over the middle of the magnet no action is observed, and the filings are there arranged as they would be over any non-magnetic substance.

412. **Laws of magnetic attraction and repulsion.**—When the two poles of a magnet are compared as to the action they exert

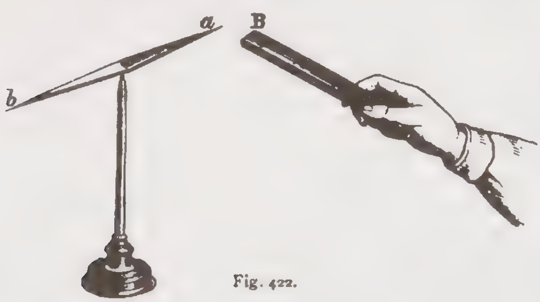


Fig. 422.

upon iron, they seem to be completely identical. This identity is however, only apparent: for if to the same pole of the magnetic needle (fig. 422) the two poles of a bar magnet held in the hand be successively presented, the curious phenomenon is observed that if the pole *a* of the needle is attracted by pole B of the bar, it is,

on the contrary, repelled by the other pole of the latter; which shows that the poles of the bar are not exactly identical, for one repels the pole *a*, while the other attracts it. The same difference may be ascertained to exist between the two poles of the needle *ab*; for if the same pole, B, of the bar be successively presented to the two ends of the movable needle, in one case there is repulsion, in the other attraction.

We shall presently see that a freely suspended magnet always sets with one pole pointing to the north and the other towards the south. The end *pointing towards the north* is called in this country the *north pole*, and the other end is the *south pole*. These are also called *red* and *blue* poles respectively, the red pole being that which points to the north. The end of the magnetic needle pointing to the north is also sometimes called the *marked end of the needle*, the

Fig. 423.

other end being the unmarked end. Hence, in reference to magnetic attraction and repulsion, the following law may be enunciated :—

Poles of the same name repel, and poles of contrary name attract, each other.

The opposite actions of the north and south poles may be shown by the following experiment. A piece of iron—a key, for example—is supported by a magnetised bar, A (fig. 423). A second magnetised bar of the same dimensions, B, is then moved along the first, so that their poles are contrary. The key remains suspended as long as the two poles are at some distance, but when they are sufficiently near the key drops just as if the bar which supported it had lost its magnetisation. This, however, is not the case, for the key would be again supported if the first magnet were presented to it after the removal of the second bar.

The attraction which a magnet exerts upon iron is a reciprocal one, as is easily verified by presenting a piece of soft iron to a movable magnet; the magnet is attracted by the iron.

413. **Experiment of broken magnets.**—If we take a magnetised steel knitting-needle, AB (fig. 424), A being the north pole, and break it in the middle at the neutral line, N, where there is no appearance of magnetisation, we shall find that each of the two halves, AB′ and A′B, forms a complete magnet, the broken ends, A′,B′, being of opposite polarity—that is to say, the end B′ is a south and the end A′ a north pole. If the half AB′ be again broken, this will in turn produce two small magnets, AB″ and A″B′, with poles and a neutral

Fig. 424.

line, and so on with the other half, and, indeed, as long as the division can be carried; and if a piece be cut anywhere out of the magnet it will be a perfect magnet. It is not possible, in short, to produce a magnet which has only one kind of magnetism, or which contains more of one kind than another; in other words, we cannot procure a *unipolar* magnet. Since the smallest pieces into which a magnet can be divided by cutting or filing, or by any other means, are found to be perfect magnets, it is concluded that, if we could deal with the elementary molecules, each would be a perfect magnet.

414. **Theory of magnetism.**—Modern views of magnetism assert that it is a property of the molecules; that every molecule of

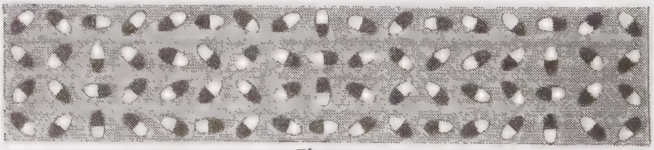


Fig. 425.

a magnetic body is in itself a complete permanent magnet, with its north pole and south pole. In the ordinary unmagnetised state, the elementary molecular magnets have no order or arrangement except that due to their mutual attractions and repulsions, so that they neutralise each other, so far as their action on an external magnetic substance is concerned. The condition of these elementary magnets

is represented in fig. 425, the black representing the south, and the white the north, poles of each. The process of magnetisation does not consist in imparting anything to the magnetic body, but in giving a definite direction to its molecular magnets. In every magnet there is a limit beyond which it cannot be more highly magnetised; this limit of magnetisation is attained when all the north poles point in one direction and all the south poles in exactly the opposite one. Between this final state of perfect arrangement and the initial state of absolute confusion there may be intermediate ones, corresponding to as many intermediate degrees of magnetisation. Fig. 426 represents such a stage.

We need not trouble ourselves with the question as to how the molecules of a magnetic substance become magnets. We have only to suppose that the magnetic character of each molecule is an

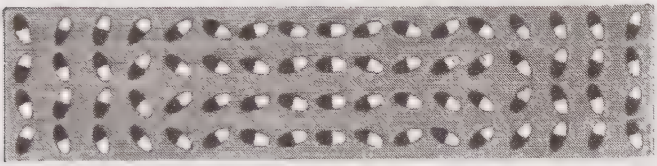


Fig. 426.

inherent and permanent property of the substance, like its hardness or opacity, or electric conductivity.

415. **Influence of magnets upon magnetic substances.**—A magnetic substance is readily distinguished from a magnet. The former has no poles; if successively presented to the two ends of a magnetic needle, *ab* (fig. 422), it will attract both ends equally, while one end of a magnet would attract the one, but repel the other, end of the needle. Magnetic substances also have no action on each other, while magnets attract or repel, according as unlike or like poles are presented to each other. Iron, nickel, and cobalt are the principal magnetic substances. Any magnetic substance may by suitable means be made into a magnet.

416. **Magnetic induction.**—A magnetic substance placed in contact with a magnet becomes itself a magnet, having a north pole nearest to the south pole of the original magnet, and a south pole at its other end, remaining so as long as the contact continues. For instance, if a small cylinder of soft iron, *ab* (fig. 427), be placed in contact with one of the poles of a magnet, the cylinder can in

turn support a second cylinder, this in turn a third, and so on, to as many as seven or eight, according to the power of the magnet. Each of these little cylinders is a magnet; if it be the north pole of the magnet to which the cylinders are attached, the part *a* will have south, and *b* north magnetism; *b* will in like manner develop in the nearest end of the next cylinder south magnetism, and so on. But these cylinders are only magnets so long as the influence of a magnetised bar continues. For, if the first cylinder be removed

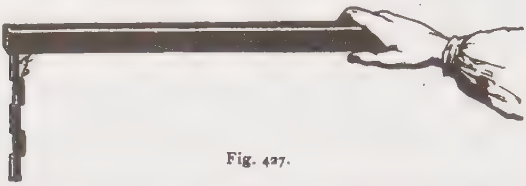


Fig. 427.

from the magnet, the other cylinders immediately drop, and retain no trace of magnetism. Hence we may have *temporary* magnets as well as *permanent* magnets.

This action, in virtue of which a magnet can develop magnetisation in iron, is called *magnetic induction* or *influence*, and it can take place without actual contact between the magnet and the iron, though the action is not so strong, as is seen in the experiment represented in fig. 428, where *ns* is a bar of soft iron.

When *ns* is removed from the neighbourhood of magnets neither end of it attracts iron filings, but when brought into the

Fig. 428.

position shown in the figure it becomes a magnet by induction, *n* being a north and *s* a south pole. Iron filings, when poured over it, cling to the ends but not to the middle.

Magnetic induction explains the formation of the tufts of iron filings which become attached to the poles. The parts in contact with the magnet are converted into magnets; these act inductively on the adjacent parts, converting them into magnets; these, again, on the following ones; and so on, producing a threadlike arrangement of the filings (fig. 420).

417. **Coercive force.**—We have seen from the above experiments that soft iron at once becomes magnetised when placed near a

magnet, but that this magnetisation is not permanent, and ceases when the magnet is removed. Steel, under like conditions, is not magnetised at all, or to a very slight extent. If two similar bars of soft iron and hard steel are each rubbed from end to end with the pole of a magnet, it will be found that the steel has become a permanent magnet, while the iron, though strongly magnetised when in contact with the magnet, has not acquired *any permanent* magnetism.

These different effects in soft iron and steel are ascribed to a *coercive force*, which, in a magnetic substance, opposes a viscous resistance to the setting of the molecular magnets in any particular direction, but when once they are set retains them in that position. In steel this coercive force is very great ; in soft iron it is very small, or even quite absent when the iron is very carefully prepared. The harder and more brittle the steel, the greater is the coercive force ; but by heating to redness and gradually cooling it becomes almost as small as with wrought iron. By straining, hammering, or twisting, a certain amount of coercive force may be imparted to soft iron, as will be explained under Magnetisation (425).

418. **Magnetic field.**—The space round a magnet in which its influence can be felt, that is, in which it can exercise magnetic induction, is called its *magnetic field.* The strength of the magnetic field at any point is the magnetic force exerted at that point, and depends upon the strength of the magnet and the distance and direction of the point from the magnet. The effect due to a magnet is often spoken of as being due to its magnetic field.

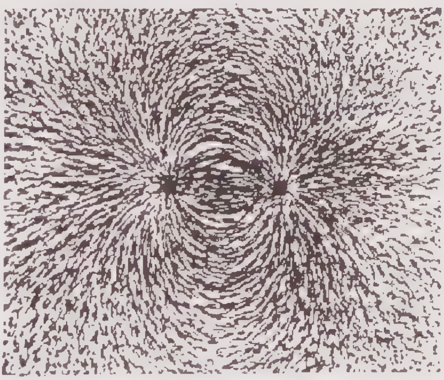


Fig. 429.

A very minute magnet, suspended so as to move freely and placed in various positions, would in each place set in a definite

direction, which would be that of the magnetic force at the place in question. If the magnet be moved in its own direction, it describes a line the tangent to which is the direction of the force due to the magnet. Such lines are called *lines of magnetic force.* Fig. 421 represents the lines of force due to a bar magnet in a horizontal plane. As the iron filings are sifted over the cardboard, each particle becomes a magnet by induction and places itself, that is, the line joining its north and south poles, in the direction of the magnetic force at the place where it falls. Its neighbours do the same, and, as north and south poles attract, the filings form into filaments which delineate the lines of magnetic force. The lines appear to start from each pole—especially from the edges near the pole—and curve round to the other. It is usual to speak of them as leaving the magnet at the north pole and returning to it at the south, so that the *direction* of a line of force is the direction in which a free isolated north pole would move.

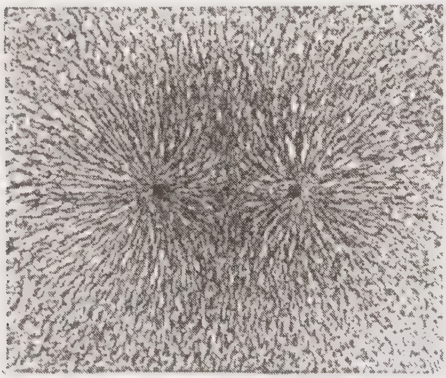


Fig 430.

Any magnet is always accompanied by its own group of lines of force, which it carries with it wherever it may be. It is well to familiarise ourselves with the idea that they are not a mere geometrical figment, but that they have a real existence.

Fig. 429 represents the field due to two opposite poles of two equal magnets, and fig. 430 that due to two equal poles of the same kind.

The strength of the field due to a magnet depends partly upon the poles of the magnet, and partly upon their distance apart. The product of these two magnitudes, viz. the strength of either pole and the distance between them, is called the *magnetic moment* of the magnet.

CHAPTER II

TERRESTRIAL MAGNETISM

419. **Directive action of the earth on magnets.**—The power of attracting iron is not the only one which magnets possess ; they have also that of setting in a certain definite direction when they can turn freely in a horizontal plane. Thus, when a magnetised needle is placed on a pivot on which it can turn freely (fig. 431), it ultimately sets in a position which is more or less north and south. If removed from this position, it always returns to it after a certain number of oscillations.

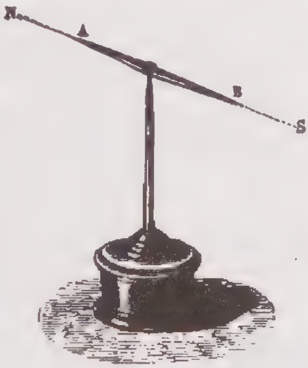


Fig. 431.

If a magnetised strip of steel is placed on a cork, and this in turn is floated on water, the magnet will, after a few oscillations, point in the same direction as the pivoted magnet, that is, nearly north and south (fig. 432). It is important in this second experiment to observe that the needle only sets in a certain direction, and that, though free to make either a forward or a backward motion, it remains in the middle of the vessel, and moves neither towards the north nor the south ; hence the force which acts upon the needle is simply *directive*, and not attractive.

Analogous observations have been made in different parts of the globe, from which the earth has been compared to an immense magnet, whose poles are very near the terrestrial poles, and whose neutral line virtually coincides with the equator.

The polarity in the northern hemisphere is called the *northern* or *boreal* polarity, and that in the southern hemisphere the *southern*

or *austral* polarity. In French works the end of a needle pointing north is called the *austral* or *southern* pole, and that pointing to the south the *boreal* or *northern* pole—a designation based on the hypothesis of a terrestrial magnet, and on the law that unlike magnetisms attract each other. In practice it will be found more convenient to use the English names, and call that end of the magnet which *points* to the north the *north* pole, and that which points to the south the *south* pole (412). That end of the needle which points to the north is often provided with a small transverse mark, and the end is accordingly spoken of as the *marked end.* Or the needle may be painted red and blue—the north end being red and the south blue. In accordance with this the northern parts of the earth must be regarded as having blue magnetism, the southern parts red magnetism, since red and blue poles attract each other.

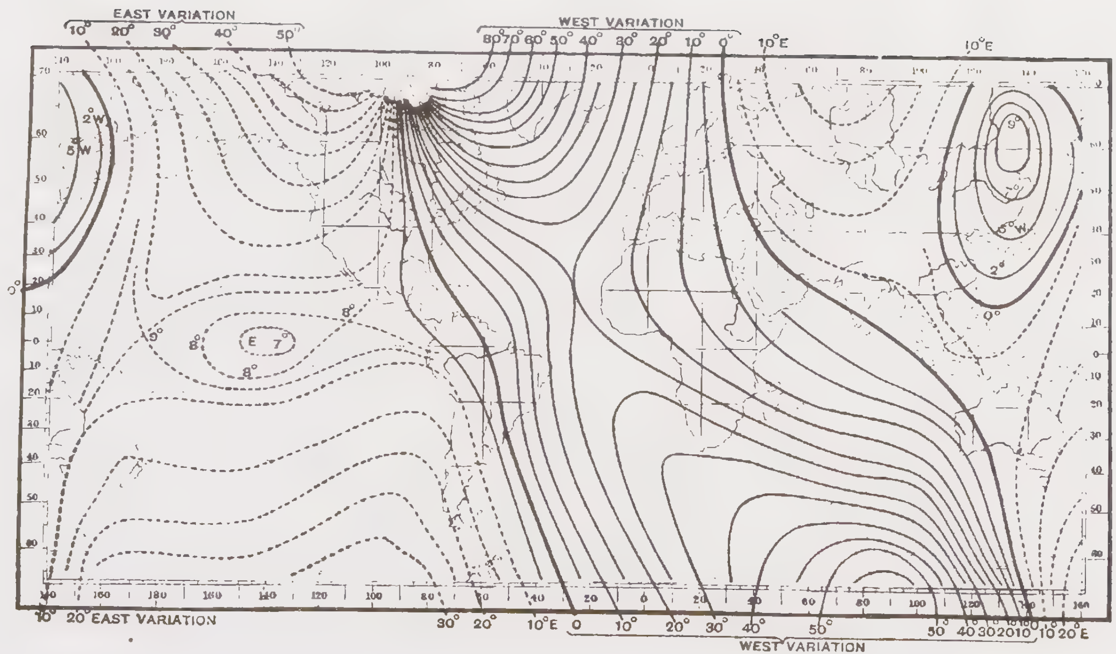
Fig. 432.

420. **Magnetic meridian. Declination.**—When a magnetic needle points towards the north, if we conceive a vertical plane, *ab*, passing through its two poles, NS, this plane is what is called the *magnetic meridian* of the place. The direction of this plane does not in general coincide with the geographical meridian of a place, which is the imaginary plane, *ns*, passing through the place and through the earth's poles. The angle (fig. 433) which the direction, *ab*, of the magnetic needle, NS, makes with the geographical meridian, *ns*, is by some called the local *declination*, and by others, and more especially by mariners, the *variation.* In other words, as the magnetic needle does not exactly point to the earth's north pole, the declination is the difference between this direction and the true north. Sometimes the north pole of the needle is to the west of the meridian, and sometimes it is to the east. In the former case the declination is said to be *westerly*, and in the latter case *easterly*.

Fig. 433.

The declination of the magnetic needle, which varies in different places, is at present westerly in Europe and in Africa, but easterly

Lines of Equal Magnetic VARIATION, 1900.



in Asia and in the greater part of North and South America. It shows, further, considerable variations from year to year even in one and the same place.

Thus, at London the needle showed in 1580 an easterly declination of 11° 36′; in 1663 it pointed due north and south; from that time the red end gradually tended towards the west, reaching the maximum declination of 24° 41′ in 1818; since then it has steadily diminished at an average rate of 7 minutes a year; it was 22° 30′ in 1850, and is now (1905) 16° 12′ W.

At Yarmouth and Dover the variation is about 40′ less than at London; at Hull and Southampton about 20′ greater; at Newcastle and Swansea about 1° 15′, and at Liverpool 1° 30′; at Edinburgh

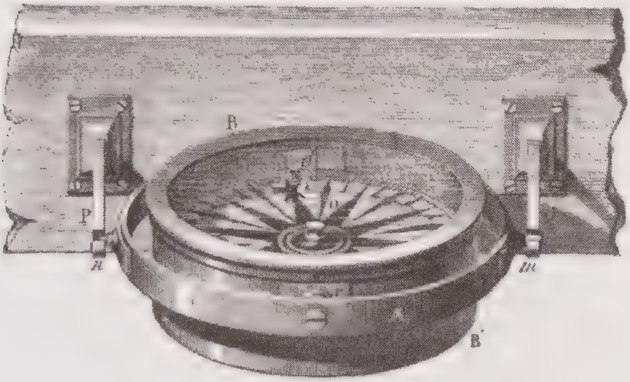


Fig. 434.

2° 5′, and at Glasgow and Dublin about 2° 25′ greater than at London.

Isogonic lines are lines connecting those places on the earth's surface in which the declination is the same. Maps on which such isogonic lines are depicted are called *declination* or *variation maps*; and a comparison of these in various years is well fitted to show the change which this magnetic element undergoes. The opposite plate represents a map in Mercator's projection giving these lines for the year 1900. It will be seen that the surface of the globe is divided by these lines into two regions: one, the smaller, in which the variation is westerly, as indicated by the continuous lines; the other in which the variation is easterly, as indicated by

the dotted lines. The thick lines are called *agonic lines*, i.e. lines of no declination. They separate regions of easterly from regions of westerly declination. Such charts are useful to the mariner as not only giving him the declination in any place, but also as showing him those regions on the globe where the declination changes most rapidly. Of these the most remarkable are the coast of Newfoundland, the Gulf of St. Lawrence, the seaboard of North America, and the English Channel and its approaches.

Besides the changes which proceed from year to year, and which are called *secular changes*, the declination of the magnetic needle undergoes *diurnal* and *annual* changes. The diurnal change does not usually exceed one-third of a degree, and is much less in winter than in summer. The declination needle also exhibits accidental variations known as *perturbations* or *magnetic storms*; these are connected with and are often manifested during the appearance of the aurora borealis. The effect of the aurora is felt at great distances. Auroras which are only visible in the north of Europe act on the needle even in the latitude of England. In polar regions the needle frequently oscillates several degrees; its irregularity on the day before the aurora borealis is a forecast of the occurrence of this phenomenon.

421. **Mariner's compass.**—The most important application of the magnetic action of the earth is in the *mariner's compass*. This is a declination compass used in guiding the course of a ship. Fig. 434 represents a view of the whole, and fig. 435 a vertical section. It consists

Fig. 435.

of a cylindrical case, BB′, which, to keep the compass in a horizontal position in spite of the rolling of the vessel, is supported on *gimbals*. These are two concentric rings, one of which, attached to the case itself, moves about the axis, *xd* (fig. 434), which plays in the outer ring, AB, while this latter moves in the supports, PQ, about the axis, *mn*, at right angles to the first.

In the bottom of the box is a pivot, on which is placed, by means of an agate cap, a thin magnetic strip, *ab*, which is the needle of the compass. On this is fixed a disc of mica, O, a little larger than the length of the needle, on which is traced a star with thirty-two branches, marking the eight points of the com-

pass, their halves and quarters. This is called the *compass card.* The branch ending in a small star, and called N, corresponds to the bar *ab*, which is underneath the disc.

In modern compasses more than one magnet is used. The magnets, each of which is a thin rectangular magnetised strip of steel, are fixed at right angles to the underside of the card, symmetrically on each side of the centre. The *binnacle* containing the compass bowl is placed close to the steering wheel, in whatever part of the ship this may be. Knowing the direction of the compass in which the ship is to be steered, the pilot has the wheel, and therefore the rudder which is controlled by the wheel, turned till the direction coincides with the sight-vane passing through a line *d* marked on the inside of the box, and parallel with the keel of the vessel.

422. **Prismatic compass.**—The *prismatic compass* is used in surveying; it differs from the mariner's compass mainly in its dimensions, and in the way in which observations are made. It consists of a shallow metal box about 2½ inches in diameter (fig. 436); the needle, which is fixed below the compass card, plays on a pivot. A metal frame, across which is stretched a horsehair, forms a sight-vane. Exactly opposite this is a right-angled or totally reflecting prism (359), P, enclosed in a metal case with an eyehole and a slit as represented at the side.

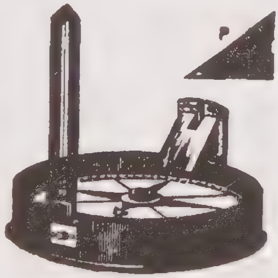


Fig. 436.

In order to make an observation the compass is held horizontally, and so that the slit in the prism, the hair of the sight-vane, and the distant object are seen to be in the same line; looking through the eyehole, the angle which the needle makes is then noted; a similar observation is made with another object, and thus the angle between them is given. The sight-vane is hinged, and can be turned down, when it presses the magnet on the pivot, thus keeping it rigid, so that the compass can be transported in any position.

The lower face of the prism is convex, and as the image is seen through this face of the prism it is magnified, and as it is seen by reflection it is reversed; hence the figures on the card must be

reversed in order that they may be read correctly through the prism.

423. **Inclination compass.**—When a steel needle supported on a vertical pivot, as represented in fig. 431, has been so accurately balanced that it is quite horizontal *before magnetisation*, it is noticed that when it is magnetised it ceases to retain its horizontal position, and the north pole dips downwards.

In order to observe this phenomenon, it is necessary to modify the mode of suspension. The needle is provided with a cylindrical steel axle passing through its centre and perpendicular to its plane, so that it can move in a vertical plane, as represented in fig. 437. The angle it forms with the horizontal plane is read off on the divided circle.

Thus arranged, the apparatus is called the *inclination compass* or *dipping needle*, and the angle which the needle makes with the horizon when it is placed so that its plane of oscillation is the magnetic meridian is called the *magnetic inclination* or *dip*.

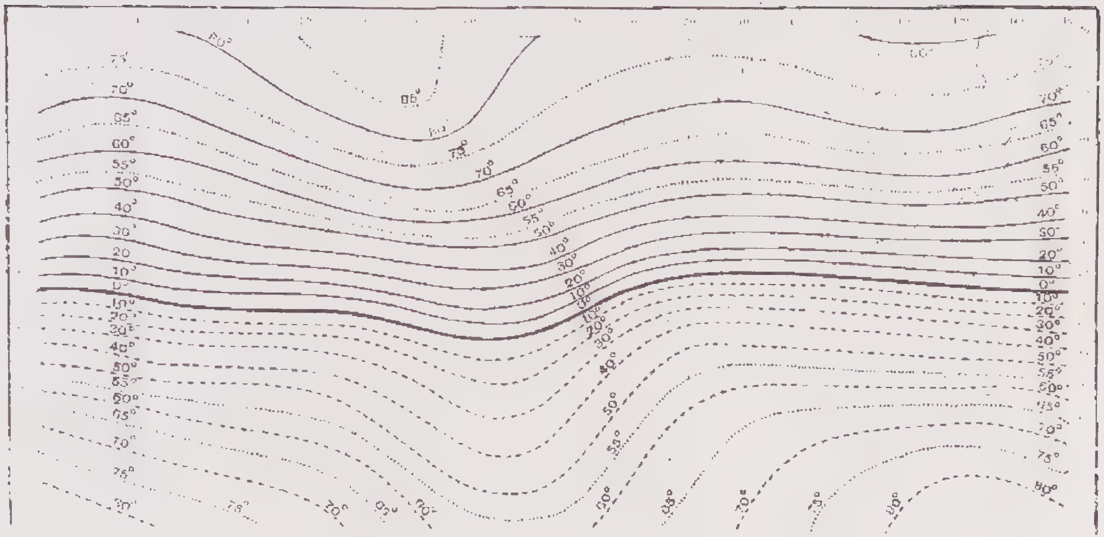
Fig. 437.

Seeing that a magnetic needle, free to move in any direction, places itself along the lines of force (418), it follows that a dip needle, since it is free to move *in the plane of the magnetic meridian*, gives us the direction of the lines of force in the field due to the earth's magnetism.

The angle of the dip, like that of the declination, differs in different localities. It is greatest in the polar regions, and decreases with the latitude towards the equator, where there is a series of places at which it is zero —that is, at which the needle is horizontal. The line joining these places is called the terrestrial *magnetic equator*. In London at the present time (1905) the dip is 67° 1′, reckoning from the horizontal line. In the southern hemisphere the inclination is again seen, but in a contrary direction—that is, the south pole of the needle dips below the horizontal line.

The terrestrial *magnetic poles* are those places in which the dipping needle stands vertical—that is, when the inclination is 90°. In 1830 the first of these, the magnetic north pole, was found by Sir James Ross in 96° 43′ west longitude and 70° north latitude.

Lines of Equal Magnetic DIP, 1900.



The same observer found in the South Sea, in 76° south latitude and 168° east longitude, that the inclination was 88° 37′. From this and other observations it has been calculated that the position of the magnetic south pole was at that time in about 154° east longitude and 75½° south latitude.

Lines connecting places on the earth's surface at which the dipping needle makes equal angles are called *isoclinic lines*. They have a certain analogy and parallelism with the parallels of latitude (42), and the term *magnetic latitude* is sometimes used to denote positions on the earth with reference to the magnetic equator. The plate facing this page is an inclination map for the year 1900, the construction of which is quite analogous to that of the map of declination.

The inclination is subject to secular variations, like the declination. At Paris, in 1671, the inclination was 75°; since then it has been continually decreasing, and in 1859 was 66° 14′. In London, also, the dip has continually diminished since 1720 by about 2·6′ per annum. In 1821 it was 70° 3′; in 1838, 69° 17′; in 1854 it was 68° 31′; in 1859 it was 68° 21′; it is now (1905) 67° 1′. It is also subject to slight annual and diurnal variations; being, according to Hansteen, about 15′ greater in summer than in winter, and 4′ or 5′ greater before noon than after.

424. **Horizontal force.**—The force of the earth's magnetism on a compass needle (the directive force) varies at different parts of the earth's surface, being greatest in the neighbourhood of the equator, and diminishing down to zero at the north and south poles. For example, the horizontal force of the earth's magnetism is twice as great at Bombay as at Portsmouth. As the force of gravity at any place is measured by the oscillations of a pendulum, so, in like manner, the oscillations of a magnetic needle afford a measure of the earth's force on a compass needle at any place. The force varies as the square of the number of oscillations in a given time.

The *magnetic elements* at any place are the declination, the dip, and the force.

CHAPTER III

METHODS OF MAGNETISATION

425. **Magnetisation by the influence of the earth.**—To *magnetise* a substance is to impart to it the properties of a magnet, that is, of attracting particles of iron, and of turning towards the north when suitably suspended. Magnetisation can be produced by the influence of the earth, by rubbing with a magnet, or by means of electricity. The best material for permanent magnets is hard steel. There is considerable difference in different specimens of iron and steel as regards their power of accepting and retaining magnetisation.

The magnetic field of the earth is powerful enough to act as a source of magnetisation. This may be illustrated by taking a rod of wrought iron and placing it in the magnetic meridian so that it makes an angle with the horizontal equal to the angle of dip. In this position the rod is parallel to the earth's lines of force and is magnetised by induction, the lower end becoming a red or north pole, and the upper a blue or south pole. Yet this magnetisation is not permanent, for, if the rod be turned upside down, the poles are inverted, since pure soft iron is destitute of coercive force (417). But if, while the rod is in the above position, it be hammered or twisted, the hammering or the twisting imparts to it a certain amount of coercive force, and it retains for some time the magnetisation thus evoked. If several thin rods thus magnetised are united so that poles of the same name are together, a tolerably powerful magnet is obtained. Steel is similarly magnetised by the earth's field, but to a much less extent.

It is this magnetising action of the earth which develops the magnetism frequently observed in steel and iron objects, such as fire-irons, gas and water pipes, railings, gates, lightning conductors, stove-pipes, lamp-posts, etc., which remain for some time in a more or less inclined position. They become magnetised with the north

pole downwards, just as if placed over the south pole of a powerful magnet. The magnetism of native oxide of iron (magnetic iron ore) has doubtless been produced by the same causes ; the very different magnetic power of different specimens being partly attributable to the different positions of the veins of ore with regard to the line of dip. The ordinary irons of commerce are not quite pure, and possess a feeble coercive force ; hence a feeble magnetic polarity is generally found to be possessed by the tools in a smith's shop, such more especially as cold chisels. Cast iron, too, has usually a great coercive force and can be permanently magnetised.

The turnings, also, of wrought iron and of steel produced by the powerful lathes of our workshops, are found to be magnetised. So, too, are rifles which have been stacked in a vertical position.

Magnetisation by magnets.—In magnetising bar magnets, and especially magnetic needles, the method generally adopted is to rub them with powerful magnets. We will describe two methods, that of *single* and that of *separate* touch.

Single touch.—The bar to be magnetised is placed on the table with the end which is to be *red* placed towards the north, and is

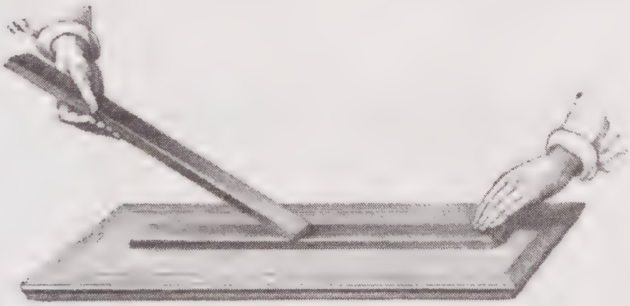


Fig. 438.

rubbed with the north or red pole or a strong magnet from north towards south (fig. 438), or, what comes to the same thing, with the south pole of the magnet from south to north, the operation being repeated two or three times. As the north pole moves over the bar, the molecular magnets are twisted round and their south poles follow the retreating north pole of the magnetising magnet. Thus the end of the bar where the rubbing ceases is of opposite

polarity to that of the rubbing pole. This method is only used for small magnets.

Separate touch.—Two equally strong magnets are required. They are held (fig. 439) with opposite poles near the centre of the bar to be magnetised and *separated*, that is, moved in opposite directions to the ends of the bar, then replaced at the centre, and the operation repeated a few times, each magnet rubbing only in one direction. The bar is then turned over and the rubbing repeated on the other side. This is a more powerful method than that of single touch, and is that employed when a dip needle has to be magnetised.

Magnetisation by means of electric currents (537) is the most powerful means of imparting magnetic properties, and is the one

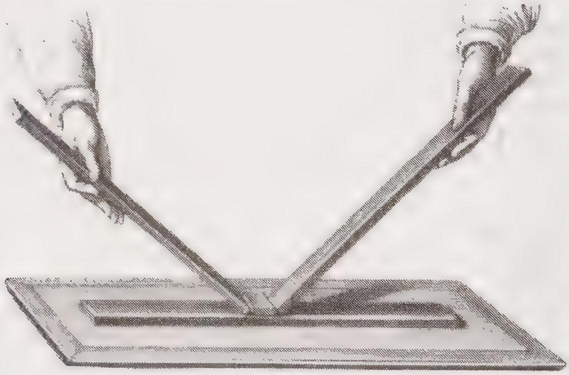


Fig. 439.

generally used for large magnets, whether bar or horseshoe. Whatever be the mode of magnetising, there is for each particular magnet a maximum of magnetisation which cannot be exceeded. When this is attained the magnet is said to be *saturated* (414).

426. **Magnetic batteries. Armatures.**—Magnetic *battery* is the name given to a system of bars joined with their similar poles together. Sometimes the bars are straight and sometimes they are curved, as shown in fig. 440, which represents a horseshoe battery. Very powerful compound magnets are now made by separately magnetising a number of thin steel plates and then riveting them together. The lifting power of such a system is not quite equal to that of the sum of the lifting powers of all the

separate magnets, for each magnet, acting inductively on the adjacent one, tends to weaken it; but it is considerably greater than that of a solid magnet of the same weight.

Magnets, whether natural or artificial, are liable to become weakened unless provided with *armatures*. These are pieces of soft iron which are placed in contact with the poles, such as the piece *ab* in fig. 440. The two poles of the magnet, A and B, produce by induction opposite poles at *b* and *a*, and these tend to maintain the magnetism of the horseshoe. The piece *ab* is also called the *keeper*; to it is suspended the weight which the magnet is intended to support. When the keeper is attached a *closed* magnet is formed, which has comparatively little external polar action, since the lines of force from A to B pass almost exclusively through the keeper.

Fig. 440.

This suggests a method of determining the strength of horseshoe magnets. If a scale pan be attached to the keeper, and weights be gradually added, the keeper will ultimately become detached; the greatest weight which such a magnet will just support measures what is called its *tractive* or *portative force*. Magnets are constructed which will support from 15 to 25 times their own weight.

Ordinary compass needles, such as are used in binnacles or for surveying, are not provided with a keeper. When not in use they should be left unclamped. Being then free to oscillate, they set in the magnetic meridian, and the earth's magnetism thus acts in a sense as a keeper.

427. **Comparison of magnetic moments.**—The moments (418) of two bar magnets may be compared by balancing the deflections of a magnetic needle which they separately produce. One of the magnets is placed at right angles to the magnetic meridian at some distance from the needle, and so that the prolongation of the axis of the bar magnet passes through the centre of the needle,

which of course is deflected. The second magnet is now placed in a similar position on the other side of the needle, similar poles facing each other. The position of the second magnet may be adjusted so that there is no deflection of the needle. The action of each magnet on the needle is then the same, and in these circumstances the moments of the two magnets are directly as the *cubes* of their distances (i.e. the distances of their centres) from the centre of the needle. Thus, if these distances are 20 and 21 inches, the moments are as 8,000 to 9,261, or the moment of the second magnet is 1·16 times that of the first.

428. **Magnetism of iron ships.**—The inductive action of terrestrial magnetism upon the masses of iron always found in ships exerts a disturbing action upon the compass needle. The *deviation* of the compass due to this cause may be so considerable as to render the indications of the needle almost useless if it be not guarded against. A full account of the manner in which deviation is produced, and of the means by which it is compensated, is inconsistent with the limits of this book, but the most important points are the following :—

i. A vertical mass of soft iron in the vessel, say in the bows, would become magnetised under the influence of the earth ; in the northern hemisphere, the lower end would be a north pole, and the upper end a south pole ; and as the latter may be assumed to be nearer the compass needle, it would act upon it. So long as the vessel was sailing in the magnetic meridian this would have no effect ; but in any other direction the needle would be drawn out of the magnetic meridian ; and a little consideration will show that when the ship was at right angles to the magnetic meridian the effect would be greatest. This error, due to *vertical induction*, would disappear twice in swinging the ship round, and would be at its maximum twice ; hence the deviation due to this cause is known as *semicircular deviation.*

ii. When an iron or steel ship is being built, each plate is magnetised by the earth's induction, and the induced magnetism is increased and rendered more or less permanent by the hammering and riveting the plate undergoes. Thus the ship when complete acts like a huge magnet. If the ship has been built in a N. and S. direction with head to north, she will have red magnetism in the bow near the keel, and blue magnetism in the stern near the deck. Semicircular error of the compass is caused by this magnetism as the ship swings.

iii. Horizontal masses, again, such as deck-beams, are also acted upon inductively by the earth's magnetism, and their induced magnetism exerts a disturbing influence upon the magnetic needle. The effect of this horizontal induction will disappear when the ship is in the magnetic meridian, and also when it is at right angles thereto. In positions intermediate to the above the disturbing influence will attain its maximum. Hence in swinging a ship round there would be four positions of the ship's head in which the influence would be at a maximum, and four in which it would be at a minimum. The effect of horizontal induction is accordingly spoken of as *quadrantal deviation.*

iv. *Heeling error.*—The effect of iron beams on a compass, when a vessel *heels over* under the influence of wind or sea, is to cause a deviation proportional to the amount of heeling.

The maximum deviation due to heel is when the ship's head is north or south by the compass, and it vanishes when the ship's head is east or west.

The influence of these various causes may be ascertained by the process of 'swinging ship.' This consists in comparing the indications of the ship's compass with those of a standard compass on shore. The ship is hauled or steams round with her head to the various points of the compass, and the readings of the compass in various positions are compared.

From this comparison a table of *deviations* is compiled, showing the reading of the ship's compass for every point of the true compass. One school of navigators content themselves with steering by the use of this table; others prefer to correct their compass by compensating the action of the iron of their vessel by magnets and masses of soft iron in the manner now briefly described.

The *semicircular deviation*, which is chiefly caused by the permanent magnetism, is corrected by magnets placed in the binnacle fore and aft and transversely.

The *quadrantal deviation* caused by the iron beams is corrected by hollow cast-iron globes placed on a level with the compass needle.

The *heeling error* is corrected by a magnet placed in a vertical position in the centre of the binnacle.

BOOK VIII

ON ELECTRICITY

CHAPTER I

FUNDAMENTAL PRINCIPLES

429. **Electricity.**—Electricity is a powerful physical agent which manifests itself mainly by attractions and repulsions, but also by luminous and heating effects, by violent shocks, by chemical decomposition, and many other phenomena. Electricity is evoked in bodies by a variety of causes, among which are friction, pressure, chemical action, heat, and magnetism.

Thales, 600 B.C., knew that when *amber* was rubbed with silk it acquired the property of attracting light bodies, such as feathers, pieces of straw, etc., and from the Greek name of this substance (ἤλεκτρον, *electron*) the term *electricity* has been derived. Six centuries afterwards, Pliny wrote of amber, 'When the friction of the fingers has imparted to it heat and life, it attracts pieces of straw as a magnet attracts particles of iron.' This is nearly all the knowledge left from ancient times; it was not until almost the end of the sixteenth century that Dr. Gilbert, physician to Queen Elizabeth, called attention to this property of amber, and showed that it was not limited to amber, but that other bodies, such as sulphur, wax, glass, etc., also acquired the property of attracting light bodies when they were rubbed or struck with flannel or with catskin.

To make this experiment, a glass rod, or a stick of sealing-wax or shellac, is held in the hand, and rubbed with a piece of flannel, or with the skin of a cat; it is then found that the parts rubbed have the property of attracting light bodies, such as pieces of silk, wool,

feathers, paper, bran, gold leaf, etc., which, after remaining a short time in contact, are again repelled (fig. 441). Not only have the substances thus rubbed the property of attracting light particles, but they also become luminous in the dark; they give sparks, and present a number of phenomena, the cause of which is described under the general term *electricity*, which was first introduced by Gilbert.

For instance, if a rod of glass is warmed, and rubbed in a dark room with a warm silk handkerchief, a crackling noise will be heard and sparks seen as the silk passes over the glass. If the glass is held near the face, a curious tickling sensation is produced, due to the hairs of the face and head being attracted by the electrified rod. If some mercury is sealed in an exhausted glass tube, a pale luminosity is seen to follow the mercury when it is shaken in the tube.

Fig. 441.

However slow may have been the progress of the science of electricity in ancient times and in the middle ages, its progress during the eighteenth and nineteenth centuries has been extremely rapid. In the last seventy or eighty years more especially the new facts discovered have been so numerous and remarkable, and their applications so curious and important, that electricity has been compared to a kind of fairy of whom it was only necessary to ask miracles to have them realised.

430. **Electroscopes. Electric pendulum. Proof plane.**—In order to ascertain whether bodies are electrified or not, instruments called *electroscopes* are used. The simplest of these, the *electric pendulum* (fig. 442), consists of a small pith ball attached by means of a silk fibre to a brass rod resting on a glass support. To find whether a body is electrified or not, it need only be presented to an electric pendulum; in the first case there is attraction, while in the second case there is not. Yet the electric pendulum is not very sensitive, and would not be affected by a body only feebly charged with electricity. More complicated and more delicate

apparatus must then be had recourse to, which will be described afterwards (438).

The electrification produced on a body by friction—for instance, that excited on a rod of shellac by rubbing it with flannel—resides on the surface of the part which has been rubbed, and may be transferred to the surface of another body. A *proof plane* is a convenient means of doing this. It consists of a disc of gilt paper or thin metal, fastened to the end of a thin shellac or ebonite rod. If a

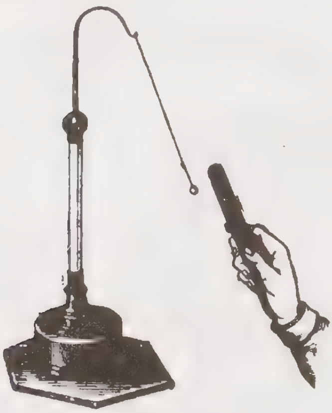


Fig. 442.

Fig. 443.

proof plane is allowed to touch an excited rod of shellac and is then brought near to the electric pendulum, the pith ball behaves exactly as it did when the shellac was approached, only the action is not so powerful.

431. **Distinction of the two kinds of electricity.**—If electricity is developed on a glass rod by friction with silk, and the rod is brought near an electric pendulum (fig. 442), the ball will be attracted to the glass, and after momentary contact will be repelled (fig. 443). By this contact the ball becomes electrified, and so long as the two bodies retain their electricity repulsion follows when they are brought near each other. If a stick of sealing-wax, electrified by friction with flannel or fur, is brought near to another electric pendulum, the same effects will be produced : the ball will fly towards the wax, and after contact will be repelled. Two bodies which have been charged with the same electricity repel each other. But the

electricities respectively developed in the preceding cases are not the same. If, after the pith ball has been touched with an electrified glass rod, an electrified stick of sealing-wax and an electrified glass rod are alternately advanced towards it, the pith ball will be *attracted* by the former and *repelled* by the latter. Similarly, if the pendulum is charged by contact with electrified sealing-wax, it will be *repelled* when this is presented to it, but *attracted* by the approach of the electrically excited glass rod.

In the above experiments the rubber as well as the substance rubbed is electrified by the friction. That this is the case, and that the electricities developed on the rubber and on the substance rubbed differ from each other, may be conveniently shown by means of two discs, one of glass, fixed to an insulated handle of glass, and the other of wood covered with a padding of silk (fig. 444) similarly insulated; if these are rubbed together, and then presented separately to an electrified pith ball, the ball will be attracted by the one disc and repelled by the other.

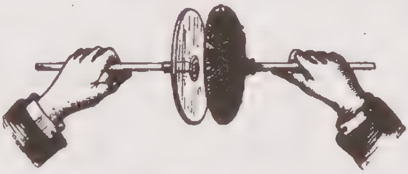


Fig. 444.

On experiments of this nature, Dufay first made the observation that there are two different electricities: the one developed on glass by rubbing it with silk, the other on shellac by friction with flannel.

432. **Hypothesis of two electricities.**—The most convenient of the various hypotheses which have been made to account for electrical phenomena is that of Symmer, an English physicist.

He assumes that every body contains an indefinite quantity of a subtile imponderable matter, which is called the *electric fluid.* This fluid is formed by the union of two fluids—the *positive* and the *negative.* When they are combined they neutralise each other, and the body is then in the natural or neutral state. By friction, by chemical action, and by several other means, this neutral fluid may be decomposed and the two fluids separated; but one of them can never be excited without a simultaneous and equal excitation of the other. When two substances are rubbed together the electric fluid of each is decomposed. The positive fluid of the first goes over to the second and the negative of the

second to the first, the result being that the first becomes *negatively* electrified and the second *positively*. The two electricities were formerly called *vitreous* and *resinous*, but the terms *positive* and *negative*, first used by Franklin, are now more generally employed. This distinction is merely conventional ; it is adopted for the sake of convenience, and there is no other reason why resinous electricity should not be called positive electricity.

Electricities of the same kind repel each other, and electricities of opposite kinds attract each other. The electricities can circulate freely on the surface of certain bodies which are called *conductors*, but remain confined to certain parts of others, which are called *non-conductors* (434).

433. **Electric attraction and repulsion.**—Adopting this two-fluid theory, the qualitative and quantitative laws of electric attraction and repulsion may be stated as follows :—

I. *Two bodies charged with the same electricity repel each other ; two bodies charged with opposite electricities attract each other.*

II. *The repulsion or attraction between two small electrified bodies is in the inverse ratio of the square of the distance between them.* That is to say, that if two bodies be charged to a certain extent with electricity, they will attract or repel each other with a certain force according as the electricities are different or are the same ; and if the distance between them be increased to twice or thrice the original amount, the force, whether of attraction or repulsion, will be one-fourth or one-ninth of what it was originally.

III. *The distance remaining the same, the force of attraction or repulsion between two electrified bodies is directly as the product of the quantities of electricity with which they are charged.* Thus, if the quantity of electricity with which a body is charged is twice or thrice its original amount, it will exercise on another charged body twice or three times the attractive or repulsive force.

The first of these laws follows from the experiment described above (431) ; the truth of the second and third laws was experimentally established by Coulomb.

434. **Conductors and non-conductors.**—When a glass rod, rubbed at one end, is brought near an electroscope, that part only will be found to be electrified which has been rubbed ; the other end will produce neither attraction nor repulsion. The same is the case with a rod of shellac or of sealing-wax. In these bodies electricity does not pass from one part to another—they do not *conduct*

electricity. Experiment shows that when a metal has received electricity in any of its parts, the electricity instantly spreads throughout its entire surface. Metals are hence said to be good *conductors* of electricity.

Bodies have, accordingly, been divided into *conductors* and *non-conductors*. This distinction is not absolute, and we may advantageously consider all bodies as offering a certain *resistance* to the passage of electricity which varies with the nature of the substance. Those bodies which offer little resistance are conductors, and those which offer great resistance are non-conductors or *insulators*; electric *conductivity* is thus the inverse of electric *resistance*. We are to consider that between conductors and non-conductors there is a *quantitative* and not a *qualitative* difference; there is no conductor so good but that it offers some resistance to the passage of electricity, nor is there any substance which insulates so completely but that it allows some electricity to pass. The transmission from conductors to non-conductors is gradual, and no sharp line of demarcation can be drawn between them.

In this sense we must understand the following table, in which bodies are classed as *conductors*, *semi-conductors*, and *non-conductors*; those bodies being conveniently designated as conductors which, being held in the hand and applied to an electroscope charged with either kind of electricity, discharge it almost instantaneously; semi-conductors being those which discharge it in a short but measurable time—a few seconds, for instance; while non-conductors effect no perceptible discharge, even in the course of a minute.

Conductors	*Semi-conductors*	*Non-conductors*
Metals.	Alcohol and ether.	Dry oxides.
Graphite.	Powdered glass.	Air and dry gases.
Acids.	Dry wood.	Dry paper.
Water.		Silk.
Snow.		Diamond and precious stones.
Vegetables.		India-rubber.
Animals.		Glass.
		Sulphur.
		Resins.

435. **Insulating bodies. Electrification of conductors.**—Bad conductors are called *insulators*, for they are used as supports for bodies on which electricity is to be retained. A conductor

remains electrified only so long as it is surrounded by insulators. If this were not the case, as soon as the electrified body came in contact with the earth, which is a good conductor, the electricity would pass to the earth. A body is insulated by being placed on a support with glass feet, or on a cake of resin or gutta-percha, or by being suspended by silk threads. No bodies, however, insulate perfectly ; all electrified bodies lose their electricity more or less rapidly by means of the supports on which they rest. Glass is in itself a very perfect insulator, but it is always somewhat hygroscopic, and the aqueous vapour which condenses on it affords a passage for the electricity : the insulating power of glass is materially improved by coating it with shellac or copal varnish. Dry air is a good insulator ; but, when the air contains moisture, this condenses on the supports of the electrified body and conducts electricity, and this appears to be the principal source of the loss of electricity.

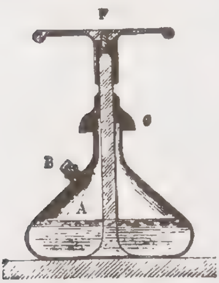


Fig. 445.

When it is required to insulate a conductor of any kind, such an insulator as that of Mascart (fig. 445) is useful. A metal plate, P, is fixed to the top of a glass rod which is fused to the bottom of a conical glass vessel (fig. 445) whose mouth is shielded by an ebonite cover. The vessel contains strong sulphuric acid, a highly hygroscopic substance, so that the stem, A, is always dry.

It is owing to their great conductivity that metals do not become electrified by friction when held in the hand. But if they are insulated, and then rubbed, they give good indications. This may be seen by the following experiment :—A brass tube is provided with a glass handle (fig. 446) by which it is held, and it is


Fig. 446.

then rubbed with dry silk or flannel. On presenting the metal to the electric pendulum (fig. 442), the pith ball will be attracted. If the metal is held in the hand, electricity is indeed produced by friction just as before, but it immediately passes through the body into the ground.

The experiment may also be conveniently made with the insulated brass sphere represented in fig. 449. If this is held by the stem, and the sphere is flapped with a dry silk handkerchief, it becomes strongly electrified.

This may further be illustrated by the following instructive experiment:—A glass cylinder containing mercury, M, insulated by resting on a slab of paraffin, P, fig. 447, is in metallic connection with an electroscope, E (438). A dry glass rod being slowly immersed the leaves do not diverge; but they do so as the rod is withdrawn, and the divergence increases until the rod is completely removed. The electrification of the mercury is imparted to the electroscope by the conductor; on bringing the rod near the electroscope the leaves collapse again, and the same result ensues if the rod is placed in the mercury. This experiment shows thus that a liquid metal may be electrified by friction, and that the electrification on the glass is equal and opposite to that in the mercury.

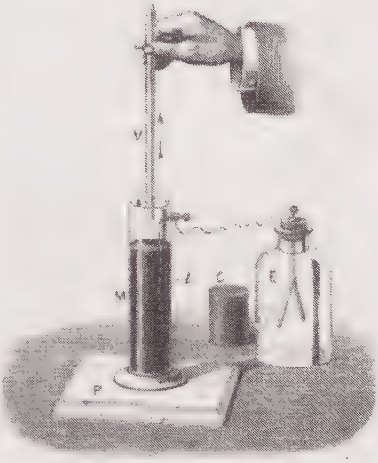


Fig. 447.

Electrification by contact is also due to conductivity; for when an insulated unelectrified conductor is made to touch a charged conductor, a portion of the charge on the latter passes at once to the former. If the two bodies have the same area and the same shape, two brass spheres of the same diameter, for instance, the electricity is equally distributed on the two; but if the bodies differ in shape or area the electricity is unequally distributed.

436. **Law of the development of electricity by friction.**—Whenever two bodies are rubbed together, the two electricities are developed at the same time and in equal quantities—one body takes the positive, and the other negative electricity. This may be best proved by the following simple experiment devised by

Faraday :—A small flannel cap provided with a silk thread is fitted on the end of a stout rod of sealing-wax (fig. 448), and rubbed round a few times. When the cap is removed by means of the silk thread, and presented to a pith-ball pendulum charged with positive electricity, the latter will be repelled, proving that the flannel is charged with positive electricity ; while, if the shellac is presented to the pith ball, it will be attracted, showing that the shellac is charged with negative electricity. Both electricities are present in equal quantities ; for if the rod is presented to the electroscope before removing the cap, no action is observed. The same result is shown by the glass and silk discs described above (431).

Fig. 448.

The kind of electricity developed on any particular body by friction depends on that by which it is rubbed. Thus, glass becomes negatively electrified when rubbed with catskin, but positively when rubbed with silk. So, too, sulphur when rubbed with the hand becomes negatively electrified, but rubbed with gun-cotton it is positively electrified. In the following list the substances are arranged in such an order that each becomes positively electrified when rubbed with any of the bodies following, but negatively when rubbed with any of those which precede it :—

1. Catskin.	5. The hand.	9. Resin.
2. Flannel.	6. Wood.	10. Sulphur.
3. Glass.	7. Metals.	11. Gutta-percha.
4. Silk.	8. India-rubber.	12. Gun-cotton.

A strip of pyroxylin or gun-paper, when drawn through the fingers, is an admirable means of producing negative electricity.

437. **Distribution of electricity on the surface of bodies.**—When a body is electrified, all the electricity goes to the surface, where it is accumulated as an extremely thin layer, tending constantly to escape, and flying off, in short, when it is not retained by any obstacle. This may be demonstrated by the following experiment, which is due to Biot.

A brass globe, fixed to an insulating support, is provided with two brass hemispherical envelopes which fit closely, and can be separated by glass handles. The sphere is electrified, and

the two hemispheres are brought in contact with each other and with the sphere. On rapidly removing them (fig. 449), the coverings will be found to be electrified, while the sphere is in its natural condition, and indicates no electricity. Thus in removing, so to say, the surface of a body, all the free electricity it contained is also removed, which shows clearly that the electricity is on the surface. That electricity resides solely on the surface is further proved by the fact that two metal spheres of the same diameter, but one of them solid and the other hollow, become equally charged when, one having been given a charge from some source, the two are brought into contact and then separated. This is proved by placing them successively at the same distance from a gold-leaf electroscope (438). It is thus found that each produces the same amount of divergence in the leaves, showing that it is not the mass

Fig. 449.

but the extent of surface which determines the charge that a conductor can acquire. Coulomb made this experiment with a brass sphere and a wooden one of the same diameter covered with gold leaf.

The same point may also be illustrated by means of the following apparatus (fig. 450). Two tinplate rings, *e*, about eight to ten inches in diameter, are connected together by four thin vertical tinplate bands, *a*, *b*, *c*, *d*, and by twenty-four vertical wires; with the exception of two, the latter are not shown, so that the interior of the apparatus may be seen. To each of the vertical bands a strip of paper is fastened both inside and out, and a similar pair of strips is suspended to a cross bar. If this apparatus is insulated and connected with an electric machine at work, the outer paper strips are repelled, while those in the interior show no signs of electric repulsion.

Franklin placed a long chain in a metal teapot, to the spout of which were suspended two pith balls. The teapot was insulated and electrified. On drawing out the chain by a silk string he found that the divergence of the pith balls diminished, but was restored to its original amount when the chain was brought back. Here there was no alteration in the mass of metal concerned in the experiment, but the extent of surface was changed.

This influence of the surface may be further illustrated by the experiment represented in fig. 451. In the ebonite tube, R, a metal tube, *m*, is inserted, provided with two paper strips. The open end of *m* is dipped in soap solution, and after being taken out it is charged with electricity so that the strips are almost

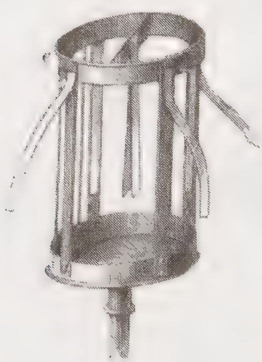


Fig. 450.

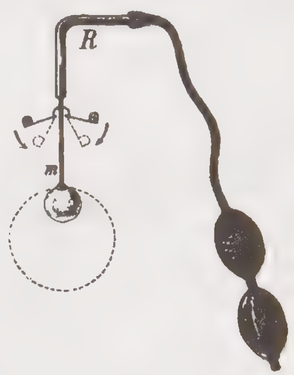


Fig. 451.

horizontal; by carefully working an india-rubber bellows, such as is used for a spray producer, a soap bubble is blown at the end of *m*, and as its volume increases the leaves fall together. On carefully detaching the tube from the ebonite, air passes out, the bubble contracts, and in the same degree the divergence of the leaves increases.

One of the most remarkable illustrations of the distribution of electricity on the surface is that employed by Faraday, who made a large cubical wooden frame, 12 feet in the side, and covered it with sheet lead. This conducting chamber was provided with door and window and was insulated from the ground. It could be connected with a powerful electric machine in full work. 'I

went into the cube,' said Faraday, 'and lived in it, but though I used lighted candles, electrometers, and all other tests of electrical states, I could not find the least influence upon them, or indication of anything particular given by them, though all the time the outside of the cube was powerfully charged, and large sparks and brushes were starting from every part of its outer surface.'

438. **Gold-leaf electroscope.**—The *gold-leaf electroscope* is a small but delicate apparatus for ascertaining whether a body is electrified, and, if so, with what kind of electricity it is charged. It consists of a tubulated glass shade (fig. 452), the neck of which is closed by a cork. In this is fitted a brass rod terminating at the top in a knob, and at the bottom in two strips of gold leaf. The neck, the cork, and the upper part of the shade are coated with a thick layer of sealing-wax varnish, which is a solution of sealing-wax in spirits of wine. The object of this coating is to improve the insulating qualities of the glass. Glass is, indeed, a bad conductor, but it is very hygroscopic (291)—that is, it readily attracts aqueous vapour from the air, and thus becomes coated with a layer of moisture, which renders its surface a conductor (435). When covered with varnish this evil is removed, for varnish, which for electric purposes is usually made of sealing-wax, is not hygroscopic.

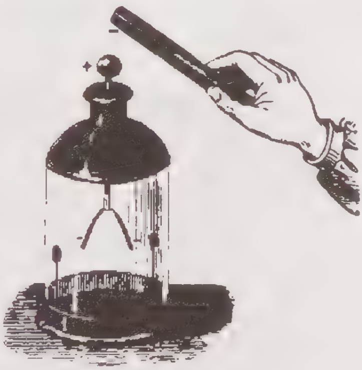


Fig. 452.

The air in the inside is dried by quicklime, or by chloride of calcium, or by pumice stone soaked in strong sulphuric acid, and on the inside of the shade there are two strips of tinfoil communicating with the ground.

When the knob is touched with a body charged with either kind of electricity, the leaves diverge. To ascertain whether the charge is positive or negative we charge a shellac rod with negative electricity by rubbing it with flannel, and by means of a proof plane transfer some of the electrification to the cap of the electro-

scope. If the divergence of the leaves increases we infer that the electroscope was charged with negative electricity. If the divergence diminishes the original charge was probably positive, but not certainly so. For confirmation we take a positive charge by means of the proof plane from a glass rod which has been rubbed with silk and communicate it to the electroscope, the leaves of which will now diverge further, showing that the original charge was positive.

The electroscope is, however, usually charged and the tests made by induction. For the mode of doing this see paragraph 444.

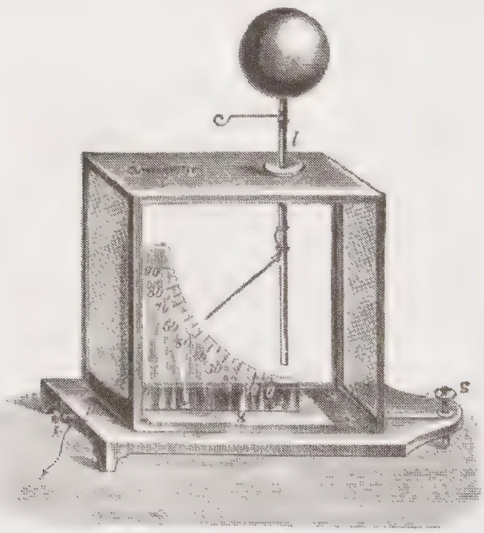


Fig. 453.

The electroscope is sometimes used as a measuring instrument or *electrometer*, the angle of divergence of the leaves being measured. This is done by placing behind them a graduated scale. For very small charges, the angle of divergence may be taken as proportional to the charge communicated to the instrument, but this proportionality no longer holds when they increase.

A convenient form of electroscope, and one which when constructed on a smaller scale lends itself to projection by the magic

lantern, is represented in fig. 453. It consists of a square sheet-metal case, the front and back of which are closed by glass and the sides by wire gauze. The metal rod, *l*, provided with a metal sphere and hook, passes through an insulator in the top, and to it is attached a thin strip of aluminium foil. When the sphere is electrified the foil is repelled, and the divergence can be measured on a mica scale.

For small degrees the deflection is a measure of the quantity of electricity imparted to the sphere, and the instrument may thus serve as an *electrometer.*

439. **Electric screens.**—The property of electricity of residing on the surface is applied in *electric screens.* If it be desired to protect anything, such as a delicate gold-leaf electroscope, from accidental injury from a discharge, it is sufficient to enclose it by a cage of wire gauze (fig. 454). It is unaffected by even powerful discharges from an electric machine placed near it. This principle has been applied in the protection of buildings from lightning discharges (484).

Fig. 454.

440. **Electric tension.**—When accumulated on the surface of bodies, electricity tends to pass off with an effort which is known as *tension* or *electrostatic pressure.* This increases with the quantity of electricity. So long as it does not exceed a certain limit, it is balanced by the resistance presented by the small conducting power of air when it is dry. If the electrostatic pressure increases sufficiently, this resistance is overcome, and the electricity springs off to an adjacent body with a sound, and in the form of a bright spark. In moist air the tension is small, for the electricity passes away almost as rapidly as it is produced, owing to the moisture condensing on the supports, which thus become good conductors of electricity. In very rarefied air, on the contrary, where there is little resistance, electricity passes off, presenting the appearance of a luminous glow.

441. **Influence of the shape of a body on the distribution of electricity. Electric density. Effect of points.**—The manner in which electricity is distributed on the surface of a body varies with its shape. If it is a sphere, the charge is everywhere the same, as might indeed be predicted, and which may be readily confirmed by means of the *proof plane* (430). This is successively applied to

different parts of the electrified body, and, after each contact, is presented to an electroscope. If the body is a sphere the divergence of the leaves is in each case the same, which shows that the disc has taken the same charge of electricity from each part of the sphere, and therefore that the distribution of the electricity is uniform.

This is not the case if the electrified body is more or less elongated; for instance, a kind of ovoid shape, as shown in fig. 455. In this case the proof plane takes a greater charge the nearer it is applied to the elongated end, and at this end itself the charge removed is greatest. This variation in the quantity of electricity in various parts is spoken of as being due to varying *electric density*, which is defined as the quantity of electricity on unit area.

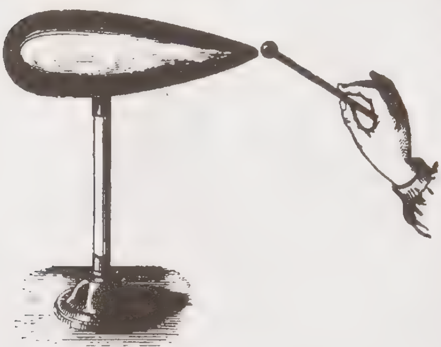


Fig. 455.

The *electrostatic pressure* at any place (440) can be shown to be proportional to the square of the electric density in that place, and since the density is greatest at points, the electric pressure is also greatest there, and is sufficient to overcome the resistance of the air, and allow electricity to escape. It is, in fact, observed that metal bodies provided with a point quickly lose their electricity, and if the hand be held over such a point, a sort of wind or draught is felt (455). If this takes place in darkness, a kind of luminous *brush* appears on the top of the point, which is known as the *brush discharge* (fig. 478).

The action of flames on electrified bodies is like that of ordinary points, but is more complete; flames are, in fact, very acute points. The readiest and most effectual method of depriving an electrified non-conductor of its charge of electricity is to pass the flame of a spirit lamp over its surface.

This property of points on electrified conductors, of allowing electricity to escape, has been called the *power* or *property of*

points; and in electric experiments we meet with numerous instances in which it comes into play. The action of points has also a most important application in lightning conductors (484).

The quantity of electricity which may be imparted to a conductor is limited. For as the charge increases the density increases, and therefore the electrostatic pressure (which varies as the square of the density) increases very rapidly, and presently overcomes the insulating power of the air. When this limit is reached any further charge given to the conductor escapes into the air.

442. **Potential.**—Instead of making the experiment with the proof plane in the manner described in the last article, let it be attached to one end of a long fine wire which is connected with an electroscope (438) at a considerable distance. If now the plane is placed in contact with the charged conductor (441), a certain divergence of the leaves is produced, which is a measure of the charge of electricity. And if the plane is in contact with any part of the ovoid the divergence of the leaves of the electroscope is the same, showing that the charge it receives is everywhere the same. This then is an experimental fact which our previous notions are insufficient to explain; it is different from either electric pressure or electric density. We require the introduction of a new conception, which is that of electrical *potential*.

This may be defined as being a property in electricity which is analogous to that of temperature in heat or to that of difference of level in hydrostatics; bodies at different potentials are analogous to bodies at different temperatures, or to liquids at different levels. If a body at one temperature is connected with a body at the same temperature there is no change, but if the temperatures are different a transfer of heat sets in and continues until both bodies are at the same temperature. In like manner, when the bodies at the same electric potential are connected, whatever their dimensions, there will be no passage of electricity from one to the other; but if their potentials are different, then, when they are connected either directly or by the intervention of a wire, electricity will pass from the one at higher to the one at lower potential until their final potentials are the same; this potential depending on the original charges and potentials of each of the bodies.

The term 'potential' was originally introduced into electric science out of considerations arising from the mathematical treatment of the subject. Its use is justified by the clearness with which it brings out the relations of electricity to work.

If we have an insulated metal sphere such as P or N in fig. 457, and this be charged, it will produce in its neighbourhood an *electric field*, the strength of which diminishes as the distance from the sphere increases, until, at a certain distance, no electric effects are produced, or, at any rate, they are too feeble to be manifested in any way, and this would be the limit or boundary of the field.

Suppose now we have a small insulated sphere, which will be called *unit sphere*, charged with the same kind of electricity as the large one, and at a distance which is great compared with the size of the sphere. If we move the sphere to any given point nearer the large one, we must do a certain amount of work on it against the repulsion of the two electric charges. We may then say that the work required to be done against electric forces in order to move unit of positive electricity from an infinite distance up to this point is called the potential at this point.

If in the above case the sphere were charged with negative electricity, then, instead of its being needful to do work in order to bring a unit of positive electricity towards it, work would be done by electric attraction, and the potential of the point near the charged sphere would thus be negative. The potential at any point may also be said to be the work done against electric force in moving unit charge of negative electricity from that point to an infinite distance.

The amount of work required to move the unit of positive electricity against electric force from any one position to any other, is equal to the excess of the electric potential of the second position over the electric potential of the first. This is, in effect, the same as has been said above, for at an infinite distance the potential is zero. Here it is immaterial along which path the unit charge is moved, whether by the shortest one or not ; just as, in the analogous case of moving a body against gravity, the work done only depends on the initial and final positions of the body moved.

We cannot speak of potential in the abstract, any more than we can speak of any particular height without at least some tacit reference to a standard of level. Thus, if we say that such and such a place is 300 feet high, we usually imply that this is its height as measured from the level of the sea. So, too, we refer the longitude of a place to some definite meridian, such as that of Greenwich, either expressly or by implication.

In like manner we cannot speak of the potential at any point without at least an implied reference to a standard of potential.

This standard is usually the earth, which is taken as being at zero potential or the same as the potential at an infinite distance. If we speak of the potential at a given point, the difference between the potential at this point and the earth is meant.

As water only flows from places at a higher to places at a lower level, so also electricity only passes from places at a higher to places at a lower potential, the direction being always such that the value of the potential tends to diminish. If an electrified body is placed in conducting communication with the earth, electricity will flow from the body to the earth, if the body is at a higher potential than the earth; and from the earth to the body, if the body is at a lower potential. If the potential of a body is higher than that of the earth, it is said to have a positive potential; and if at a lower potential, a negative potential. A body charged with *free negative electricity* is at a *lower* potential than the earth; one charged with *free positive electricity* is at a *higher* potential.

443. **Electric capacity and charge.**—The capacity of any conductor is measured by the quantity of electricity which it acquires when its electric potential is raised by unity.

We may illustrate the relation between capacity and potential by reference to the analogous phenomenon of heat. In the interchange of heat between bodies at different temperatures, the final result is that heat only passes from bodies of higher to bodies of lower temperature. So also electricity only passes from bodies of higher to bodies of lower potential. Potential is as regards electricity what *temperature* is as regards heat, and might indeed be called *electric temperature.* We may have a small quantity of heat at a very high temperature. Thus a short thin wire heated to incandescence has a far higher heat potential, or temperature, than a bucket of warm water, but the latter will have a far larger quantity of heat. A flash of lightning represents electricity at a very high potential, but the quantity is small.

When the charge or quantity of electricity imparted to a body increases, the potential increases in the same ratio; so that, calling Q the quantity of electricity, C the capacity, and V the potential, we have $Q = CV$; that is to say, the charge, or quantity of electricity that any body possesses, is the product of the potential into the capacity. Hence, with a given charge of electricity, Q, the greater the capacity the lower is the potential, and the smaller the capacity the higher is the potential.

While there is a close analogy between heat and electricity, as

regards capacity, there are important differences ; thus the capacity of a body for heat is influenced by the temperature, being greater at higher temperatures, while the capacity of a body for electricity does not depend on the potential.

Calorific capacity is proportional to a specific coefficient which varies with the material, but is independent of the shape, while electric capacity varies with the shape of the conductor but not with its material, provided electricity can move freely over it. Calorific capacity is unaffected by the proximity of other bodies, while electric capacity depends on the position and shape of adjacent conductors.

CHAPTER II

ACTION OF ELECTRIFIED BODIES ON UNCHARGED BODIES; INDUCED ELECTRICITY. ELECTRIC MACHINES

444. **Electricity by influence or induction.**—A charged insulated conductor, since it produces an electric field all round it, acts on uncharged bodies placed near in a manner analogous to that of the action of a magnet on soft iron; that is, to use the language of the two-fluid theory, it decomposes the neutral electricity, attracting the opposite, and repelling the like kind of electricity. The

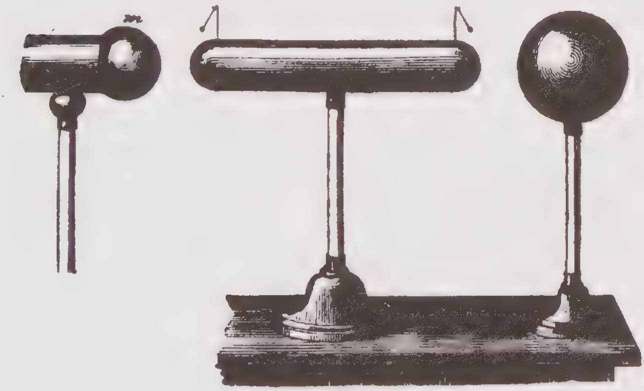


Fig. 456.

action which is exerted not only through air, but also through insulating substances like gutta-percha, glass, resin, etc., is said to take place by *influence* or *induction.*

The phenomena of induction may be demonstrated by means of the apparatus represented in fig. 456. On the left hand of the figure is the prime conductor of the electric machine, which, as we shall afterwards see, is usually charged with positive electricity;

on the right is a brass cylinder, insulated by being placed on a glass support, and provided with small pith-ball pendulums, suspended by linen threads, which are conductors. When the cylinder is brought near the prime conductor, the pendulums are found to diverge. If a sealing-wax rod which has been rubbed with flannel is presented to the pendulum nearest the electric machine, it will be repelled, showing that it is charged with the same electricity as the rubbed sealing-wax; that is, with negative electricity. If in like manner a glass rod which has been rubbed with silk is brought near to the other end of the cylinder, the pendulum there is also repelled, which shows that it is charged with positive electricity. The electricities thus produced are equal in quantity, for if the cylinder is removed the pendulums cease to diverge, since two electricities recombine, and the body is restored to the neutral state. The best way of testing the distribution of electricity on the cylinder is by means of a proof plane (430) and gold-leaf electroscope. The proof plane is allowed to touch various parts of the cylinder, and becomes charged with the electricity which happens to exist at the part touched. The charge is then transferred to the electroscope and its sign examined by glass rod or sealing-wax. In this way we find that the positive and negative charges reside chiefly at the ends. Near the middle there is no charge at all.

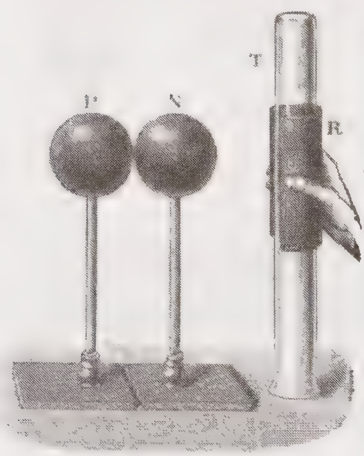


Fig. 457.

If another uncharged conductor, an insulated sphere for example, is brought near to the cylinder (fig. 456), it is influenced by the positive electricity at the end of the cylinder and becomes charged by induction with negative on one side and positive on the other.

The operation of induction may also be illustrated by the experiment represented in fig. 457, in which the glass cylinder, T, becomes positively electrified

by friction with the silk rubber, R. P and N are two copper spheres on insulating glass stems. If, while the two spheres are touching, the electrified cylinder is placed near them, the sphere nearest the glass becomes negatively electrified, and the further one is positively electrified, and if the spheres be separated, P will be found to have a free positive and N a free negative charge. These charges may be tested by a gold-leaf electroscope.

This *electrification by influence*, or *induction* as it is called, which is produced by an electrified body on bodies in the neutral state, explains a host of phenomena. In order to explain all its effects, it is important to inquire what takes place when the insulated cylinder, in the above experiment, is placed for a short time in contact with the ground, while it is still under the influence of the machine. Suppose, for instance, the further end be placed in contact with the ground, the positive electricity will escape, while the negative remains, held by the attraction of the opposite electricity of the machine. If now connection with the ground be broken and the cylinder be moved away from the influence of the machine, the pendulums will diverge, and, as can be easily verified, owing to their being charged with negative electricity. Even if the end nearest the machine be connected with the ground, the result is still the same. The negative electricity does not pass into the ground; it is the positive which still escapes; the negative being attracted by the contrary electricity of the machine, on interrupting the communication with the earth, the cylinder remains charged with negative electricity.

Light bodies, such as pith balls, are more easily attracted by an electrified body when they rest on a conducting support in connection with the ground than when they are on an insulator. For in the former case the repelled electricity escapes into the ground.

Thus a body can be charged with electricity by induction as well as by conduction. But in the latter case the charging body loses part of its electricity, which remains unchanged in the former case. The electricity imparted by conduction is of the same kind as that of the electrified body, while that excited by induction is of the opposite kind. To impart electricity by conduction, the body must be quite insulated, while in the case of induction it must be in connection with the earth, at all events momentarily.

The phenomena of induction, illustrated above by means of an insulated cylinder placed near the prime conductor of an electric

machine, may be further exhibited by a gold-leaf electroscope and a charged body such as an excited stick of shellac. The electroscope takes the place of the cylinder, and the experiment illustrates the way in which an electroscope is generally employed for the purpose of testing a charge. For example, let the shellac be rubbed with flannel and brought near to the cap of the electroscope. The leaves diverge with negative electricity, the cap being positive, and the divergence increases as the rod is brought nearer. With the shellac at a definite distance let the cap be momentarily earth-connected by being touched with the finger ; the negative electricity disappears, the leaves collapse, and the electroscope is at zero potential. Remove the shellac ; the leaves open again, this time with positive electricity, and the potential rises to some positive value. Thus, from the negatively charged shellac a free positive charge has, by induction, been communicated to the electroscope. To give the electroscope a negative charge from the same source a direct transfer is effected by means of a proof plane. Similarly, from a positively charged body—for instance, a glass rod rubbed with silk—either a negative or a positive charge may be communicated to the electroscope : a negative charge by induction, a positive charge by the aid of the proof plane.

There are many respects in which the phenomena of magnetic differ from those of electric induction. In magnetism, when the inducing body and that submitted to its action are placed in direct contact, there is no change except that the action is stronger, nor does the inducing magnet lose any of its strength. In electricity, on the contrary, when the inducing and induced bodies are brought in contact, conduction takes place ; both bodies are charged with the same kind of electricity, which is shared between them in proportion to their capacities (443), and accordingly the inducing body loses some of its electricity. It is thus possible to obtain a body charged with one kind of electricity only ; while in magnetism we cannot perform the analogous operations—we cannot get detached *unipolar* magnets. Again, the magnetic induction is limited to a very small number of substances, virtually to iron, steel, nickel, and cobalt, while electric induction takes place in all substances.

445. **Faraday's experiments.**—The following experiments of Faraday, which are often known as 'the ice-pail experiments,' from the vessels with which they were originally made, are of great importance.

1. A metal cylinder is placed on an insulating stand and charged

with, say, positive electricity. On testing with proof plane and electroscope we find that no part of the charge is inside the cylinder; it is entirely on the outside and chiefly near the edges. If the charge is directly communicated to the inside, the result is the same—the charge does not stay there, but is found on testing to be entirely outside.

2. The cylinder is again charged. One end of a fine wire is attached to the cap of the electroscope, and the other end to a glass rod in such a way that it can be made to touch any part, inside or outside, of the cylinder. When contact is made the leaves diverge, and the divergence is exactly the same whatever part of the cylinder be touched. This is expressed by saying that all parts of the cylinder are at the same potential. In the inside, where the electric density (441) is zero, the potential is the same as at the edges, where it has its maximum value.

3. The cylinder is connected by a wire to the cap of the electroscope. It is not charged. When a brass ball, A (fig. 458), insulated by a silk thread, is charged with, say, positive electricity and lowered into the cylinder, the leaves of the electroscope diverge, as can be shown, with positive electricity, and the divergence increases as the ball descends until a certain depth is attained, when there is no further increase. The divergence now remains constant whatever be the position of the ball, and when the inside and outside are tested with the proof plane they are found to be charged with negative and positive respectively. If the ball is withdrawn the leaves collapse and there is no electrification on the cylinder; the quantities of negative and positive electricity developed on the two surfaces were accordingly equal to each other.

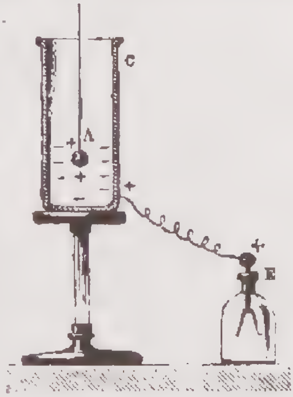


Fig. 458.

4. The ball charged with positive electricity is brought, as before, into the cylinder and is allowed to touch the inside; there is no alteration, not even a momentary one, at the instant of contact, in the divergence of the leaves of the electroscope; but if the ball is

withdrawn it will be found to be discharged, as is also the inside of the cylinder, while the outside is charged with positive electricity. The whole of the charge of the ball has been transferred to the cylinder. We learn also from this experiment that the charge induced by the ball is equal to the inducing charge, for if it were greater or less there would be *some* change in the divergence of the leaves at the moment of contact. We further notice that, although there can be no free charge inside a conductor, there may be an induced charge.

5. If, when A has been lowered to the position represented in fig. 458, the cap of the electroscope is momentarily touched, the leaves collapse, the positive electricity on the outside of C disappears, and the potential falls to zero. Inside C, however, the charges undergo no change, the positive on A and the negative on the inner surface of C being equal to each other. If A is withdrawn, the negative passes to the outside of C, and the leaves diverge to the same extent as before, proving that the potential is now as much below zero as it was before above. If A touches C the whole system is discharged.

Faraday's cylinder furnishes an excellent means of proving that the quantities of opposite kinds of electricity produced when bodies are rubbed together are equal; for if the rod and cap in fig. 448 are placed in the cylinder after being rubbed, no divergence of the leaves is produced. Nor is there any if both cap and rod are simultaneously in the cylinder, not touching each other, and this is the case in whatever position they are placed in the cylinder. If either of them, however, is withdrawn, the leaves of the electroscope at once diverge, and, as may easily be shown, with the same electricity as that of the body left in the cylinder, but the divergence ceases when the other is brought back into the cylinder. Whichever be removed, the extent of the divergence of the leaves is the same, although the electricities are different.

446. **Ramsden's electric machine.**—The first electric machine was invented by Otto von Guericke, the inventor also of the air-pump (148). It consisted of a sphere of sulphur, which was turned on an axis by means of one hand, while the other hand, pressing against it, served as a rubber. Resin was afterwards substituted for the sulphur, which in turn Hawksbee replaced by a glass cylinder. In all these cases the hand served as rubber (fig. 475); and Winckler, in 1740, first introduced cushions of horsehair covered with silk as rubbers. At the same time Bose

collected the electricity excited on the glass by friction, by means of an insulated cylinder of tin plate. Lastly, Ramsden, in 1760, replaced the glass cylinder by a circular glass plate, which was rubbed by cushions. The present form of the machine is but a modification of Ramsden's.

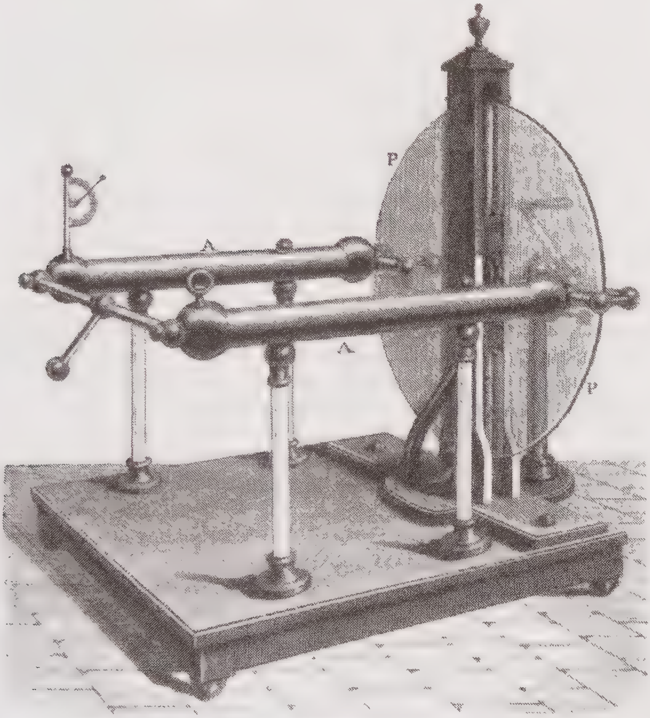


Fig. 459.

Between two wooden supports (fig. 459), a circular glass plate, P, about a yard in diameter, is suspended by an axis passing through the centre, and turned by means of a glass handle. The plate revolves between two sets of *cushions* or *rubbers*, of leather or of silk, one set above the axis and one below, which, by means of screws, can be pressed as tightly against the glass as may

be desired, by which means the plate becomes electrified on both sides. In front of the plate also are two brass rods, provided with a series of points in the sides opposite the glass ; these rods are fixed to two large metal cylinders, A A, which form the *prime conductor*. The cylinders are insulated by glass supports, and are connected with each other by a smaller rod.

The action of the machine is thus explained. By friction with the rubbers, the glass becomes positively, and the rubbers negatively, electrified. If the rubbers were insulated, they would receive a certain charge of negative electricity which it would be impossible to exceed, for the tendency of the opposed electricities to reunite would be equal to the power of the friction to decompose the neutral fluid. But the rubbers communicate with the ground by means of bands of tinfoil, fixed to the supports not shown in the figure, and consequently, as fast as the negative electricity is generated, it passes off. The positive electricity of the glass acts then by induction on the conductor, attracting the negative electricity and repelling an equal quantity of positive. The negative electricity is discharged by the points upon the glass plate, and the prime conductor remains charged with positive.

As thus described, the electric machine yields only positive electricity ; it may, however, be arranged so as to give negative electricity. For this purpose the feet of the table are insulated by being placed on thick slabs of resin, of glass, of gutta-percha, or of sulphur, and the conductors are connected with the ground by a metallic chain. This allows the electricity of the positive conductors to escape, while the negative electricity of the rubbers accumulates on the supports and on the bands of tinfoil.

447. **Quadrant electroscope.**—The electric condition of the prime conductor is indicated by the *quadrant electroscope*, commonly called *Henley's electrometer*, which is represented in fig. 459 attached to the conductor. This is a small electric pendulum, consisting of a brass rod, to which is attached an ivory or cardboard scale (fig. 460). In the centre of this is a small straw index, movable on an axis, and terminating in a pith ball. Being attached to the conductor, the index rises as the machine is charged, ceasing to rise when the limit is attained. When the rotation is discontinued the index falls rapidly if the air is moist ; but in dry air it only falls slowly, showing, therefore, that the loss of electricity in the latter case is less than in the former.

Hence, in moist weather experiments with the electric machine

are difficult to perform. All parts of the apparatus must be carefully warmed by an open fire, and the supports and plate must be rubbed with hot cloths. It is, indeed, by the supports that the greater part of the electricity is lost.

The rubbers are commonly made of leather stuffed with horsehair. Before use they are coated either with powdered *aurum musivum* (tin sulphide) or amalgam. The action of these substances is not very clearly understood. Some consider that it merely consists in promoting friction. Others, again, believe that a chemical action is produced, and assign, in support of this view, the peculiar smell noticed near the rubbers when the machine is

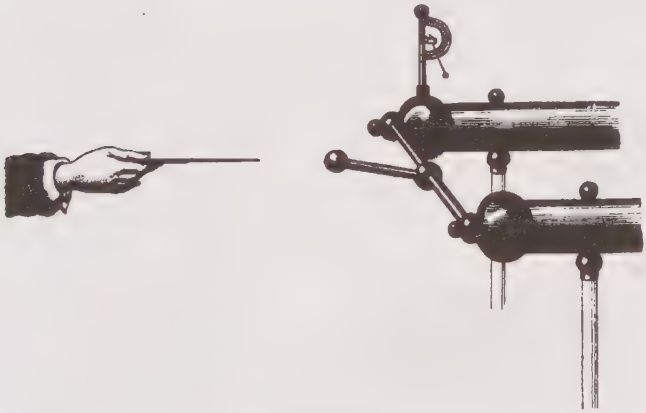


Fig. 460.

worked. Amalgams, perhaps, promote most powerfully the disengagement of electricity. *Kienmayer's amalgam* is the best of them; it consists of 1 part of tin, 1 of zinc, and 6 of mercury.

Whatever precautions be taken to avoid the loss of electricity, or however rapidly the machine be turned, it is impossible to exceed a certain limit of charge and potential of the prime conductor. For, as the electricity accumulates, its density at any point and hence the electrostatic pressure increase too, and very soon its tendency to escape exceeds the resistance offered by the air and the supports of the conductors. From this moment the loss of electricity equals the production, and hence the potential can never

exceed a certain limit, which is indicated by the electrometer remaining stationary, although the rotation is continued.

If, moreover, the maximum effect is desired, the machine must not be placed too near walls or furniture on which there are sharp points. Thus, if a point or the flame of a candle be presented to the prime conductor of a machine in action, as represented in fig. 460, the electrometer index falls, even though the point is at some distance. This is due to the fact that the positive electricity of the machine induces negative in the point, repelling positive through the body into the earth ; the negative flows out through the point as fast as it is produced, and, combining with the positive electricity on the prime conductor by means of which it was evoked, continually tends to bring the machine back to the neutral state.

448. **Electrophorus.**—This is a very simple apparatus invented by Volta, by means of which considerable quantities of electricity may be produced. It consists of a *cake* of resin (fig. 461), of about twelve inches diameter and an inch thick, which is placed on a metal surface, or very frequently fits in a wooden mould lined with tinfoil, which is called the *form*. Besides this, there is a brass disc, of a diameter somewhat less than that of the cake, provided with an insulating glass handle. This is called the *cover*. The mode of working this apparatus is as follows :—All the parts of the apparatus having been well warmed, the cake, which is placed in the form, or rests on a metal surface, is briskly flapped with a catskin, as shown in fig. 461, by which it becomes charged with negative electricity. The cover held by the insulating handle is then placed on the cake. The negative electricity of the cake, acting thus inductively on the cover, attracts positive electricity to the lower surface, and repels negative to the upper (fig. 462). It also attracts positive electricity to the upper side of the base,

Fig. 461.

repelling negative to the ground. If now the upper surface of the cover be touched by the finger, as shown in fig. 463, the negative electricity passes out into the ground, and the disc only retains positive electricity. Now, when the cover is raised by one hand by means of the insulating handle, and the other hand is brought near it, a smart spark passes, due to the recombination of the positive of the disc with the negative produced by its induction in the hand (fig. 464).

Fig. 462.

It was by induction that the cover became electrified, and not by any transfer of electricity; for if the cover be put down on the cake and raised again without being earth-connected, it will carry away no charge. Hence the operation may be repeated any number of times, and a succession of sparks obtained. The retention of electricity is greatly promoted by keeping the cake in the form, and placing the cover upon it. Instead of a cake of resin,

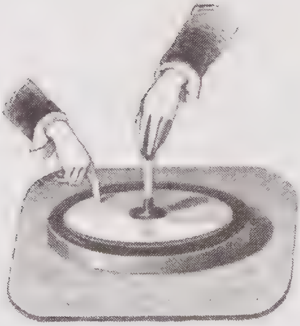


Fig. 463.

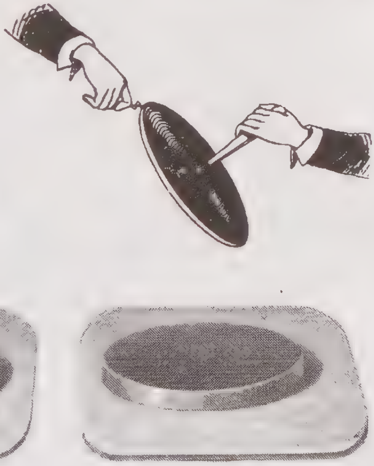


Fig. 464.

a disc of gutta-percha or vulcanite may be used, and of course, if any non-conducting material which becomes *positively* electrified by friction be used as a cake, the cover acquires the negative charge.

449. **Induction or influence machines. Wimshurst's machine.**—Several electric machines have of late been devised, in which the electricity is not continuously produced by friction, but where an initial charge is imparted as in the electrophorus, and this, by a process of continuous inductive action, goes on accumulating until very powerful effects are obtained. Such apparatus are known as *induction* or *influence machines.*

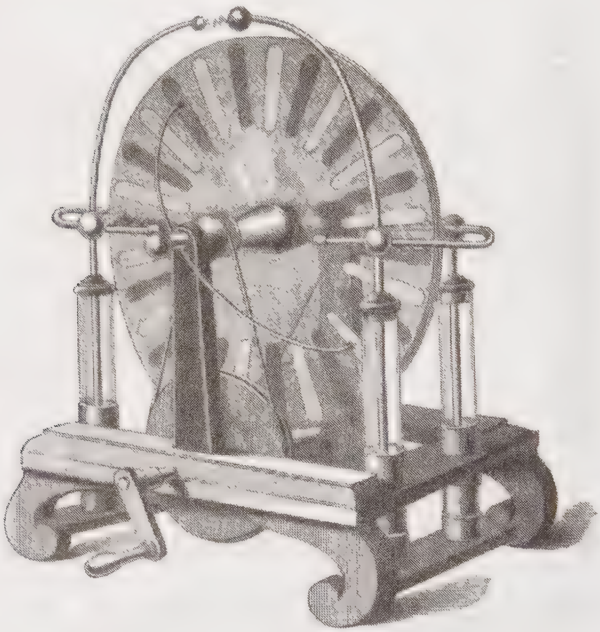


Fig. 465.

One of the most efficient of all these machines is that of Wimshurst. It consists (fig. 465) of two circular glass discs mounted on a fixed horizontal spindle in such a way as to be rotated in opposite directions at a fixed distance of not more than a quarter of an inch apart. Both discs are well varnished, and attached to the outer surface of each are narrow radial sectors of tinfoil or brass arranged at equal angular distances apart.

In the front, attached to the fixed spindle on which the discs rotate, is a bent conducting rod, at the ends of which are fine wire brushes ; twice during each revolution two diametrically opposite conductors are put in connection with each other by means of this conductor, as they just graze the tips of the brushes. At the back is a similar conducting rod at right angles to that in front, and there is a position of maximum efficiency, which is when they make an angle of 45° with the fixed collectors.

There are two forks provided with combs directed towards each other, and towards the two discs which rotate between them ; they are connected with the inner coatings of Leyden jars (465), to which are also attached the terminal electrodes or dischargers, the distance apart of which can be varied by turning the Leyden jars from which they rise.

The machine is self-exciting, and requires neither friction nor the spark from any outside exciter to start it. This is one of the

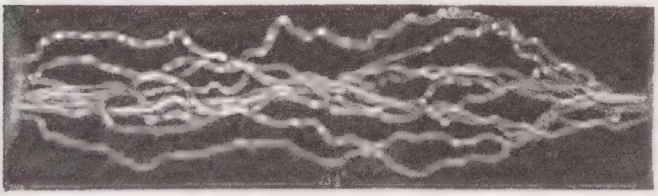


Fig. 466.

most remarkable features of this machine, that under ordinary conditions it attains its full power after the second or third turn of the handle. The initial electrification is probably obtained from chance variations of atmospheric electricity, or from the frictional resistance between brush and sector.

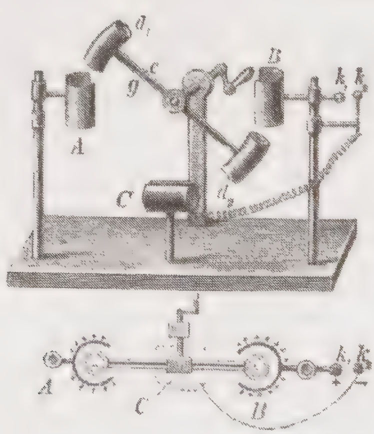
With a machine having plates 17 inches in diameter, a powerful and regular succession of sparks passes between the two electrodes when they are four to five inches apart, at the rate of two or three for every turn of the handle.

A large machine of this kind which has a plate 7 feet in diameter is calculated to give sparks between terminals 2 feet 6 inches apart, but as yet no Leyden jars (465) have been found that can stand the charge, and batteries that have successfully faced all the great historic machines give way before the enormous tension, and are pierced.

By increasing the number of plates still more powerful effects are produced. With a machine with twelve plates thirty inches in diameter, the sparks represented in fig. 466 were obtained.

It is not easy to give a satisfactory simple explanation of the action of the machine. Its inventor considers that its remarkable efficiency may be partly due to the duplex action of the apparatus, both plates being active and contributing electricity to the collecting combs, the sector-shaped plates of brass acting as *inductors* when in their position of lowest efficiency as *carriers*, and as *carriers* when in the positions at which their inductive effect is at a minimum; and as it follows, from the construction of the instrument, that the inductors of the one disc are at a position of highest efficiency when those of the other are at their lowest, and *vice versâ*, and as this applies with equal force to the sectors when considered as carriers, it also follows that the charging of the electrodes, and therefore the discharge between them, is, by mutual compensation, maintained constant.

450. **Doublers.**—The *duplicating* action of such machines may perhaps be rendered more comprehensible by the apparatus repre-



sented in fig. 467, of which the lower part shows the plan. A and B are hollow metal cylinders partially open, fixed on insulating supports; g is a stout glass tube turned by a handle, and through it

passes a copper wire, e, having at the ends cork cylinders, d_1, d_2, covered with tinfoil which is in connection with e. Inside B is a hank of cotton yarn, as there is also in the insulated cylinder C; this is connected with the knob, k_2, as B is with k_1.

A is charged positively; d_1 when inside, but not touching it, is acted on by induction, and the repelled positive at d_2 is neutralised by the points of the yarn, and B remains charged with positive electricity; d_1 passing next through the hollow cylinder C gives up its charge of negative electricity by contact with the yarn.

On further turning, d_1 and d_2 change their functions, but the same process is repeated, and we thus obtain another charge of the conductors B and C and so forth. In dry air a continuous series of sparks passes between k_1 and k_2 as long as the machine is turned. The cylinder A retains its constant charge of positive electricity, and the production of the electricity takes place by influence at the cost of the work required to overcome the attraction between A and the cylinder which is leaving it, and the repulsion between B and the cylinder which is approaching it.

The name *doubler* has been given to this and similar apparatus.

CHAPTER III

ELECTRIC EXPERIMENTS

451. **Electric spark.**—One of the first experiments made by those who see an electric machine at work for the first time is that of taking from it an electric spark by bringing the hand near the conductor. The positive electricity of the conductor

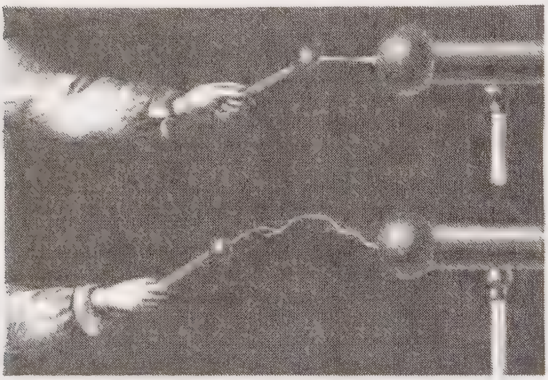


Fig. 468.

Fig. 469.

acting inductively on the neutral electricity of the body repels the positive and attracts the negative. When the difference of potential of the opposed electricities is sufficiently great to overcome the resistance of the air, they re-combine, with a smart crack and a spark. The spark is instantaneous, and is accompanied by a sharp prickly sensation, more especially with a powerful machine. Its shape varies. When it strikes at a short distance, it is rectilinear, as seen in fig. 468. Beyond two or three inches in length the spark becomes irregular, and has the form of a sinuous curve with branches (fig. 469).

452. **Insulating stool.**—A spark may be taken from the human body by the aid of the *insulating stool*, which is simply a low stool with stout varnished glass legs. The person standing on this stool touches the prime conductor, and, as the body is a good conductor, the electricity is distributed over its surface as over an ordinary insulated metallic conductor. The hair 'stands on end' in consequence of repulsion, a peculiar sensation is felt on the face, and if another person, standing on the ground, presents his hand to any part of the body, a smart crack, with a pricking sensation, is produced. If paper tassels are held in the hand, they diverge widely. Instead of such a stool, a sheet of india-rubber cloth may be used. If a person standing on an insulated stool is struck with flannel or with silk, or is brushed with a clothes-brush by one standing on the ground, the former becomes electrified ; and if he touches a gold-leaf electroscope the leaves diverge, and, as may be shown, with negative electricity.

453. **Electric chimes.**—The *electric chimes* is a bell-work which is worked by electric attraction and repulsion. It consists of three metal bells suspended from a horizontal rod, *m*, which is connected with the electric machine (fig. 470). The two bells, *b* and *c*, are suspended by light metal chains ; the middle one is suspended by silk, and is, moreover, connected with the ground by a chain. Between the bells are two small brass balls, suspended by silk threads. When the machine is worked these small brass balls are attracted by the electricity which passes by conduction to the bells *b* and *c*, and strike against them ; but being at once repelled, they strike against the middle bell, to which they give up their electricity, which thus passes into the ground. They are then again attracted, again repelled, and so the bells continue to ring as long as the electric machine is worked.


Fig. 470.

454. **Dancing puppets.**—This, like the chimes, is an application of the attractions and repulsions of electrified bodies. It consists in placing a small, very light figure of pith, loaded at the feet, between two metal discs, one connected with the ground and the

other with the electric machine (fig. 471). As soon as this latter becomes charged, the small puppet is successively attracted and repelled from one to the other disc, as if it executed of its own proper action a series of jumps.

With this we may mention the experiment of the *electric hail*, which was originally devised by Volta for the purpose of illustrating what he supposed to be the motion of hail between two clouds oppositely electrified. It consists of a glass cylinder (fig. 472), with a metal base, in connection with the earth, on which are some pith balls. The cylinder has a metal top, which is connected by a wire with the prime conductor.

When the machine is worked, the lid, becoming positively electrified, attracts the light pith balls, which are then immediately repelled, and, having lost their charge of positive electricity by being put to earth, are again attracted, again repelled, and so on, as long as the machine continues to be worked.

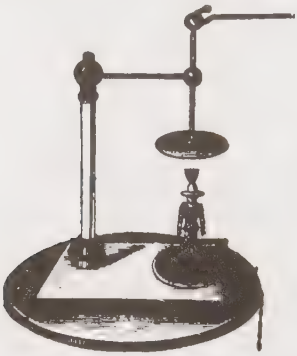


Fig. 471.

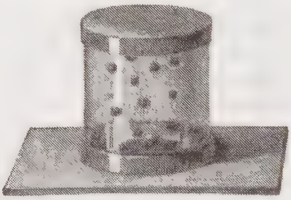


Fig. 472.

455. **Electric whirl or vane.**—The electric *whirl* or *vane* consists of four to six wires, terminating in points, all bent in the same direction, and fixed in a central cap which rotates on a pivot (fig. 473). When the apparatus is placed on the conductor, and the machine is worked, the whirl begins to revolve in a direction opposite that of the points. This motion is analogous to that of the hydraulic tourniquet (88), but, unlike that, it is not caused by a flow of material fluid, but is due to a repulsion between the electricity of the points and that which they directly impart to the air by conduction. The electricity, being accumulated on the points, where the electric density and hence the electrostatic pressures become very large, passes into the adjacent air, and, thus imparting

to it a charge of electricity, repels this electricity, while it is itself repelled. That this is the case is evident from the fact that, on approaching the hand to the whirl while in motion, a slight draught is felt, due to the movement of the electrified air; while *in vacuo* the apparatus does not act at all. This draught or wind is known as the electric *aura*. The escape of electricity in this way is analogous to the manner in which heat is transmitted in liquids (236), and is sometimes known as *electric convection*.

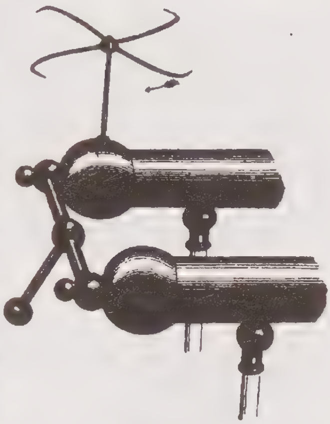


Fig. 473.

When the electricity thus escapes by a point, not only is the electrified air repelled so strongly as to be perceptible to the hand, but the current is strong enough to blow out a candle (fig. 474). The same effect is produced by placing a taper on the conductor, and bringing near it a pointed wire held in the hand (fig. 475). The current arises, in this case, from the contrary electricity

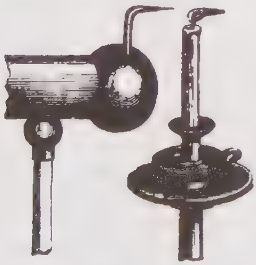


Fig. 474.

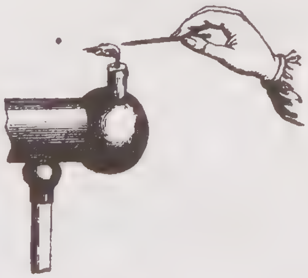


Fig. 475.

which is withdrawn through the point under the influence of the machine.

It is pretty certain that in these experiments it is not the air itself, but the particles in it, whether of dust or of moisture, which

become electrified. This may be illustrated by the following simple experiment. A glass jar is filled with dense smoke of turpentine or petroleum or of sal-ammoniac through the tube *c* (fig. 476), and the bared end of a gutta-percha-covered wire is held in it while the other end is connected with an electric machine. On giving two or three turns to the machine the smoke is rapidly deposited, and the inside becomes quite clear. Here the smoke consists of solid particles, which become polarised by induction and attract each other. They thereby become agglomerated, and fall to the bottom of the globe. Similarly air may be freed from ordinary dust. If air is freed from dust by such means or by filtration, it takes little or no charge from an electrified point. A flame acts like a point,

Fig. 476.

Fig. 477.

but in a far higher degree, owing to the conducting vapours which rise from it, and act like a host of fine points. A column of smoke acts similarly.

The *electric orrery* and the *electric inclined plane* are analogous to these pieces of apparatus.

If a small metal vessel containing water, having minute apertures through which it issues in drops (fig. 477), be suspended by a wire to the prime conductor, the water issues in jets when the vessel is electrified by working the machine, in consequence of the repulsion between the electrified vessel and the issuing water, which is electrified also.

If a wire about $\frac{1}{8}$ to $\frac{1}{4}$ of an inch in diameter, and rounded at the end, is placed on the conductor of the electric machine, which

is worked in a dark room, the electricity in streaming out illuminates the air, and a kind of luminous brush appears on the top of the point. This is known as the *brush* discharge (fig. 478).

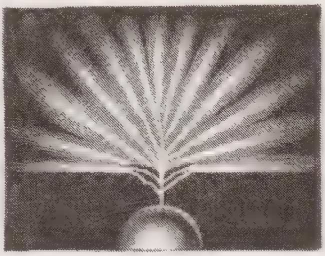


Fig. 478.

It is remarkable that the form of the brush discharge differs with the kind of electricity with which the conductor is charged; it is larger with positive than with negative electricity. With the latter the discharge has more the shape of a luminous star, or a steady glow, which is called the *glow* discharge.

It appears from other experiments also that there is a difference in the facility with which the two electricities discharge. Faraday made a pair of exactly similar forked discharging rods (fig. 479), the ends of which were provided with knobs of unequal size, kK_1 and k_1K. Each pair being at exactly the same distance from each

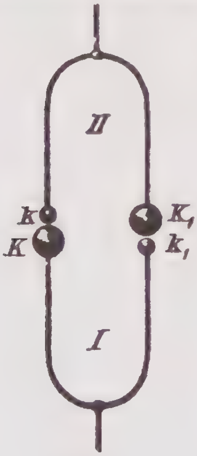


Fig. 479.

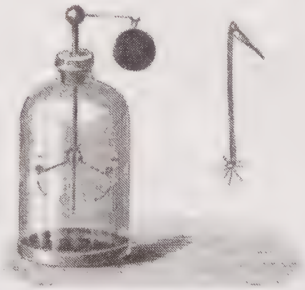


Fig. 480.

other, it was found that when the fork II was positive the discharge was between k and K, while it was between k_1 and K_1 when the fork I was positive; the striking-distance was always greater when the small knob was positive and the large one negative.

Here also may be mentioned an experiment which shows a

difference between the two electricities, and also indicates a connection between light and electricity. A polished zinc disc (fig. 480) is attached to an electroscope and charged with positive electricity, so that there is a considerable divergence of the leaves. If now the disc is exposed to the direct action of the sun's rays, or to the light from a clear blue sky, the divergence of the leaves is not appreciably lessened ; but if the experiment is repeated with a charge to the same extent of negative electricity, the leaves at once begin to fall together, and in about a minute the whole charge has escaped. The effect does not occur in the dark, and it is diminished if the sun's rays before falling on the disc have previously passed through a glass plate.

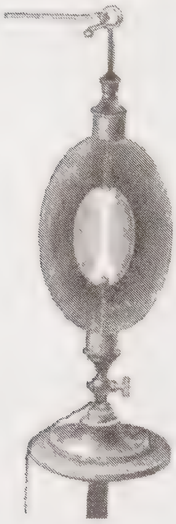


Fig. 481.

The same effect as that of sunlight is also produced by burning magnesium ribbon at a distance of a few inches from the electroscope. It is due to violet and ultra-violet rays (373), most of which are absorbed by glass. No appreciable effect is produced if the charge is positive.

456. **Electric egg.**—The influence of the pressure of the air, or rather of its non-conductivity, on the electric light may be studied by means of the *electric egg*. This consists of an ellipsoidal glass vessel (fig. 481), with metal caps at each end. The lower cap is provided with a stopcock, so that it can be screwed into an air-pump, and also into a heavy metal base. The upper metal rod moves up and down in a leather stuffing-box ; the lower one is fixed to the cap. The air in the vessel having been exhausted, the stopcock is turned, and the vessel screwed into its base ; the upper part is then connected with a powerful electric machine, and the lower one with the ground. When the machine is worked the globe becomes filled with a faint violet light continuous from one end to the other, resulting from the recomposition of the positive electricity of the upper cap with the negative of the lower. If the air be gradually allowed to enter, by opening the stopcock, the resistance increases, and the light, which appeared continuous and brilliant, is now only seen as an ordinary spark.

457. **Magic pane.**—The magic pane consists of a glass plate, one side of which is covered with several strips of tinfoil, arranged so as to form a series of metal bands, parallel and close to each other. The pane is supported vertically by two glass rods, and the upper end of the tinfoil is connected with the electric machine by a conductor, and the lower one with the ground by a chain. In this condition, if the machine is worked, the electricity will pass into the ground by the tinfoil, without any interruption ; but if a series of breaks are made in the tinfoil by cutting it away with a penknife, a spark appears at each break ; and if these breaks are so arranged as to represent a given object—a flower or a monument or words—this object is reproduced in a line of fire when the electric machine is set to work. The explanation of this experiment is really to be referred to the prodigious velocity of light which is not less than about 186,000 miles in a second ; hence in the above experiment, although the sparks are really successive, they follow each other with such rapidity as to seem simultaneous and continuous (378).

458. **Luminous globe and tube.**—The *luminous globe* is a glass globe lined on the inside with a series of small lozenges of tinfoil

Fig. 482.

placed very near each other without actually touching. The first plate is connected with an electric machine at work, and the last with the ground, upon which a series of bright sparks appears at each break in the metallic conductor.

If the small metal plates are arranged inside a glass tube in the form of a spiral from one end to the other, this arrangement forms a *luminous tube*, sometimes called the *electric serpent* (fig. 482).

Metal and glass beads threaded alternately on a silk thread render it possible to construct readily names which are luminous as long as the discharge from a machine is passed through them.

459. **Volta's cannon.**—This is not merely interesting as an experiment, but also as demonstrating an important fact—namely, that the electric spark can establish chemical action. Thus, water is formed of two gases, hydrogen and oxygen, in the ratio of one volume of the latter to two volumes of the former. Now, when an electric spark is passed through a mixture of these two gases,

they combine in these proportions, and form water. This combination is, moreover, attended by a bright flash of light and a loud report, the latter being due to the expansive force of aqueous vapour, arising from the high temperature produced by the combination.

Volta's cannon is an illustration of this property which some mixtures of gases have of being exploded by the electric spark. It is a small brass cannon, resting on an insulating support. In the touchhole is a small glass tube, and in this a brass wire with a small knob at each end (fig. 483); one of which knobs is on the outside, and the other very near, but not touching, the inside face of the cannon. When the cannon has been filled with a mixture of two volumes of hydrogen and one of oxygen, it is closed by a cork and is connected with the ground by a metal chain. If then the charged disc of the electrophorus is brought near, a spark passes to the small knob, and at the same time another inside the cannon. This latter causes the two gases to combine with a violent explosion which drives out the cork. Instead of hydrogen and oxygen, a mixture of coal gas and air may be used.

Fig. 483.

CHAPTER IV

CONDENSATION OF ELECTRICITY

460. **The Leyden jar.**—In 1745 Cunæus, of Leyden, wishing to electrify water contained in a flask, suspended to the conductor of an electric machine a wire, and then held the flask in one hand so that the wire just dipped in the water (fig. 484). The machine having been worked for some time, he accidentally touched the conductor, and in so doing received a violent shock.

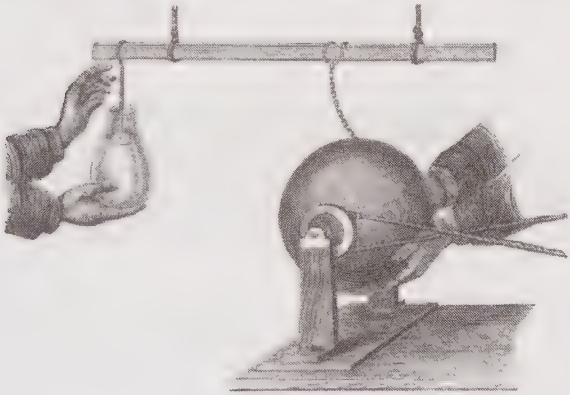


Fig. 484.

Muschenbroeck, his teacher, who repeated the experiment, received in the arms and breast a shock so violent that it was two days before he recovered from its effects ; and, writing to his friend Réaumur, he said he would not repeat the experiment for the whole kingdom of France.

In the previous year, Kleist, a German clergyman, in a private letter to a friend, described an experiment which he had made, and

which was substantially the same as the above; but it was the Dutch philosophers who investigated the conditions of success, and who gave the explanation of the phenomenon; and accordingly it is in their honour that the name *Leyden jar* is given to the apparatus to which their discovery gave rise.

461. **Electric condenser.**—It is not difficult to see that in the above experiments the water and the hand play the part of two conductors separated by the insulating glass; any arrangement in which these conditions are fulfilled would produce similar effects,

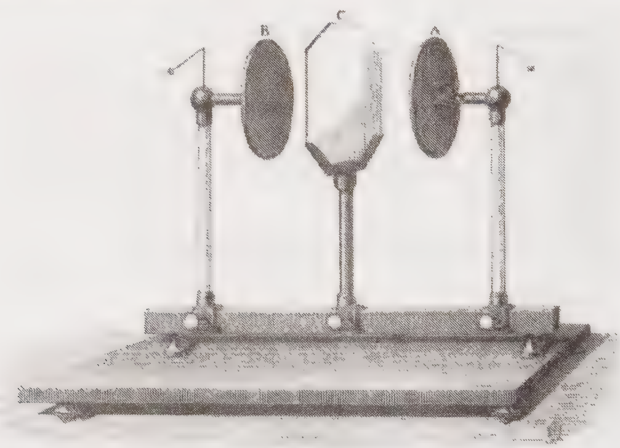


Fig. 485.

for it would have the power of accumulating or condensing electricity, from which has been derived the term *accumulator* or *condenser*.

The action of the condenser may be conveniently illustrated by reference to that of Epinus (fig. 485), which consists of two metal plates, A and B, insulated by being supported on glass legs. Between them is a plate of glass or other solid insulator, and all these can be moved along a horizontal bar and fixed in any position.

If the insulated metal plate B is connected with the prime conductor of an electric machine which we will suppose gives when worked a small but constant supply of electricity, it will acquire the potential of the machine, and the pith ball on B will be repelled to

an extent indicating this potential. If now connection with the machine is broken and the second plate A is brought near the first, the divergence of the pith ball on B is less, showing that the potential has fallen, while that on A diverges further. If the plate A is moved away, A's pith ball falls and B's rises to its original amount, indicating that B has acquired its original potential.

On now connecting the plate B with the prime conductor, while A is near it the machine must be worked some time before the divergence of the pith balls indicates that the plate has again acquired the potential of the machine. At this point equilibrium is established, and a limit to the charge is attained which cannot be exceeded, for the potential of B cannot rise above that of the machine. The effects described are more marked if the plate A is put to earth, and if the dielectric separating the two is a solid, such as glass or ebonite.

It follows from this series of experiments that the presence of the second plate has enabled the first one to take a greater charge of electricity than when it is alone—in other words, has increased the capacity (443) of the first plate. This is what is called the *condensation* or *accumulation* of electricity, and any arrangement in which one conductor, placed in connection with a source of electricity, is separated by an insulator from a second conductor in conducting communication with the earth, is called a *condenser*, the former plate being the *collecting*, and the other the *condensing* plate. The two plates are also called the armatures or coatings of the condenser.

In however varied a manner these conditions are fulfilled, we have a condenser. Thus, when an electric machine is at work, and the knuckle is held at a certain distance from the prime conductor, sparks pass across with a frequency which, with the same rate of working the machine, depends on the distance. Here, in every stage of the working, electricity is being continuously produced; but only when it has sufficiently accumulated can it discharge across the layer of air between it and the knuckle. Here the prime conductor is the source of electricity, the layer of air is the dielectric, and the knuckle is the conductor in connection with the earth.

462. **Slow discharge and instantaneous discharge.**—While the plates A and B are separated only by the glass plate C (fig. 485), and the connections interrupted, the condenser may be discharged either by a slow or by an instantaneous discharge. To discharge

it slowly, the plate B is touched with the finger and a spark passes. If A be now touched, a spark passes, and so on by continuing to touch alternately the two plates. The discharge only takes place slowly ; in very dry air it may require several hours.

An instantaneous discharge may be effected by means of the *discharging rod* or *discharging tongs* (fig. 488). This consists of two bent brass rods, terminating in knobs, joined by a hinge. If this is held in the hand as represented in fig. 488, and one knob be applied to one plate of the condenser while the arc is bent, so that the second touches the other plate, just before contact a spark passes, which is due to the reunion of the two electricities accumulated in the condenser ; no shock is felt, for the recombination

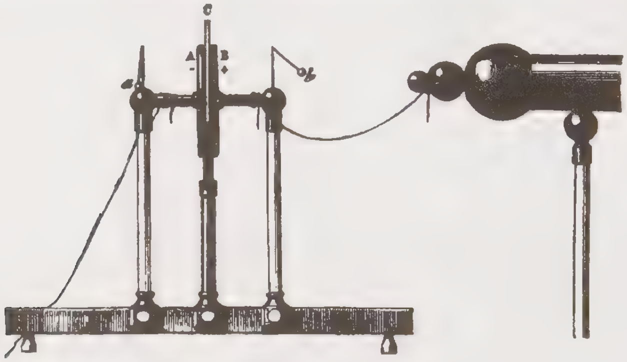


Fig. 486.

does not take place through the arms and body of the experimenter, but through the metal arc, which is a far better conductor.

463. **Amount of the charge of condensers.**—The quantity of electricity which can be accumulated in a condenser depends upon the electric potential of the prime conductor of the machine, and on the capacity of the condenser. The latter varies directly as the area of the plates, and inversely as the distance between them. There is another circumstance which influences the capacity of a condenser, and that is the nature of the insulator, or what is also called the *dielectric*, itself.

Two causes limit the quantity of electricity which can be accumulated. First, that the potential of the collecting plate gradually increases, and ultimately equals that of the machine, which

cannot, therefore, impart any more electricity, for electricity will only pass from a place at higher to a place at lower potential. The second cause is the imperfect resistance which the insulating plate offers to the recombination of the two opposite electricities; for when the force which impels the two electricities to recombine exceeds the resistance offered by the insulating plate, it is perforated and the contrary electricities unite.

The effect of charging the condenser is to put the dielectric in a state of mechanical strain from which it is always trying to release itself. The potential energy of this strain is the equivalent of the work done in charging the condenser. When the strain exceeds a certain limit, a discharge takes place through the mass of the dielectric, generally accompanied by light and sound, and with a temporary or permanent rupture of the dielectric according as it is fluid or solid. This is analogous to what takes place when a substance—glass, for instance—is exposed to a continually increasing weight; a point is ultimately reached at which the glass gives way, and the weight at that point is a measure of the resistance to fracture of the glass. In like manner, the difference of potential at which the electric discharge takes place is a measure of the electric strength of the dielectric. This dielectric strength is greater in glass than in air, and in dense than in rarefied air.

464. **Specific inductive capacity. Dielectric constant.**—Faraday made the very important discovery that the insulator in a condenser does not play the merely passive part of separating the armatures or coatings (461), but has an essential influence on the condensation of electricity. Insulators differ in the facility with which they allow inductive actions to take place in them, a property which is not the same as insulation. Thus, if a condenser be formed in which the plates or armatures are separated by a layer of air, and another with metal plates of the same area separated by a plate of paraffin of the same thickness, it will be found that, with the same source of electricity, twice as much is condensed in the latter as in the former; or, what is the same thing, if the paraffin were twice as thick as the air, that is, the plates were at twice the distance apart, it would condense as much electricity as the air condenser.

In this sense Faraday spoke of insulators as *dielectrics*, and he applied the term *specific inductive capacity* to express the varying extent to which they allow inductive actions to take place through them. The specific inductive capacity, or, as it is also called,

the *dielectric constant* of a substance, is the ratio of the charge which a condenser of that substance can acquire compared with that of a condenser, of the same dimensions, in which air is the dielectric, the difference of potential between the plates in each case being the same.

The following are the dielectric constants of some substances compared with air as unity :—

Air	1·00	Glass	3·16
Paraffin	2·00	Ebonite	3·23
Petroleum	2·05	Sulphur	3·84
Turpentine	2·30	Ether	4·56

Electrification was formerly supposed to be a property of conductors, not merely in condensers, but in the case of all its manifestations, and the space between the conductors was regarded as merely passive. Faraday's discovery was of far-reaching importance; it has led to a complete revolution of previous conceptions as to electricity; we are to look for the seat of electrification in the dielectric itself and not in the conductor.

If a positively charged body be placed near a disc of sulphur, the latter is electrified by induction, like a conductor, negatively on the anterior and positively on the posterior side. It may be assumed that by induction the individual molecules are electrified negatively on the anterior and positively on the posterior faces; in the interior of the insulator each positive is neutralised by the negative on the next molecule, so that only on the surface layers does electricity show itself. This process Faraday calls *dielectric polarisation*.

An experiment by Matteucci may be cited in support of it. He placed several thin plates of mica close together, and provided the outside ones with metallic coatings. Having electrified the system, the coatings were removed by insulating handles, and on examining the plates of mica successively, each was found charged with positive electricity on one side and negative electricity on the other.

Faraday's ideas, developed theoretically by Maxwell, have of late received remarkable confirmation from the experiments of Hertz. They reveal the close connection between light, radiant heat, and electricity, and they show that light waves, heat waves, and electric waves travel with the same velocity, and differ only in respect of the rate of vibration of the particles of the medium which transmits them.

By means of apparatus of suitable dimensions Hertz succeeded in reproducing all the ordinary phenomena of light, reflection, refraction, etc., by means of electric waves.

The new views will ultimately lead to a complete recasting of our conceptions of electricity and of the mode of presenting them. They have not, however, as yet been so far worked out in detail as to be suited for elementary instruction.

465. **Leyden jar.**—The ordinary form of the Leyden jar (460) or flask consists of a glass bottle with a wide mouth, coated inside and outside with tinfoil up to a certain distance from the bottom. The neck is provided with a stopper of hard-baked wood, through which passes a brass rod, which terminates at one end in a knob, and communicates with the tinfoil in the interior. The metallic coatings are called respectively the *internal*

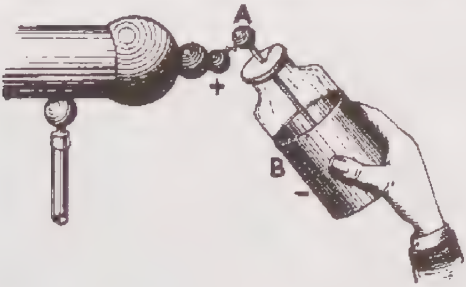


Fig. 487.

and *external armatures* or *coatings.* Like any other form of condenser, the jar is charged by connecting one of the armatures with the ground and the other with the source of electricity. When it is held in the hand by the external coating, and the knob presented to the conductor of the machine (fig. 487) which is being worked, positive electricity is accumulated on the inner, and negative electricity on the inside of the outer, coating. The reverse is the case if the jar is held by the knob and the external coating presented to the machine. The explanation of the action of the jar is the same as that of the plate condenser (fig. 485), and what has been said of this applies to the jar, substituting the two armatures for the two plates, A and B, of the condenser.

Like any other form of condenser, the Leyden jar may be discharged either slowly or instantaneously. For the latter it is held

in the hand by the outside coating, and the two coatings are then connected by means of the simple discharger (fig. 488). Care must be taken to touch *first* the external coating with the discharger, otherwise a smart shock will be felt. When it is to be discharged slowly, the jar is placed on an insulated plate, and first the inner and then the outer coating touched, either with the hand or with a metallic conductor. A slight spark is seen at each contact.

Fig. 489 represents a very pretty experiment for illustrating the slow discharge. The rod connecting with the inner coating terminates in a small bell, *d*, and the outside coating is connected with an upright metal support, on which is a similar bell, *e*.

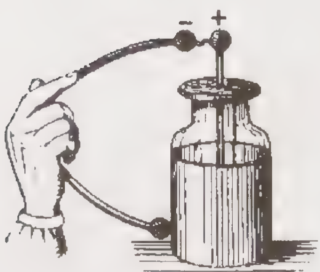


Fig. 488.

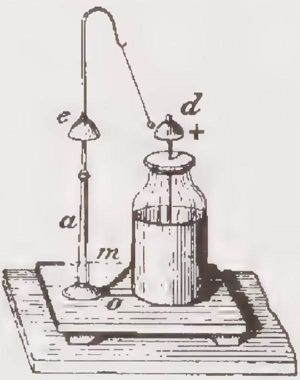


Fig. 489.

Between the two bells a gilt pith ball is suspended by a silk thread. The jar is then charged in the usual manner, and placed on the support, *m*. The internal armature contains a quantity of free electricity ; the pendulum is attracted and immediately repelled, striking against the second bell, to which it imparts its free charge. Being now neutralised, it is again attracted by the first bell, and so on for some time.

When a jar has been discharged and allowed to stand a short time, a second charge may be taken, which is due to the *electric residue* or *residual charge*. The jar may be again discharged, and a second residue will be left, feebler than the first, and so on for three or four times. The residue is greater the longer the jar has

remained charged. The magnitude of the residue further depends on the amount of the charge, and also on the degree in which the metal plates are in contact with the insulator. It seems to be due to penetration of some of the electricity into the dielectric, from which it does not at once pass to the surface when the jar is first discharged. Or, in accordance with the 'strain' theory (463), the strain to which the dielectric is subjected is relieved when the condenser is discharged. If the dielectric is *air*, the relief is absolute; there is no residual charge; but if the dielectric is glass or other solid material, the relief of the strain on connecting the coatings is only partial, and further relief (residual discharge) is obtained on again connecting the coatings.

466. **Electric battery.**—The charge which a Leyden jar can take depends on its size and the thickness of the glass. But very

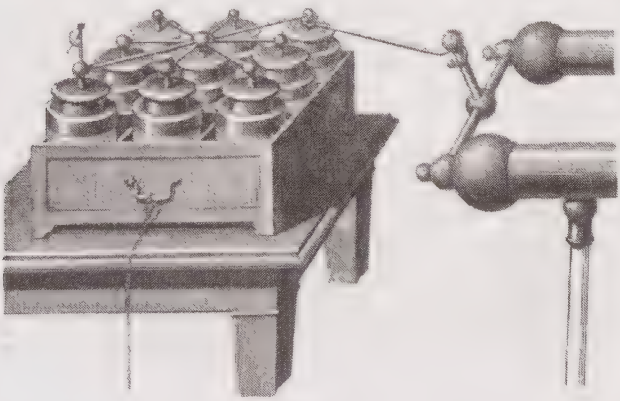


Fig. 490.

large jars are expensive, and liable to break; and when thin, the accumulated electricities are apt to discharge themselves through the glass, especially if this is not quite homogeneous, for the dielectric itself when charged is in a state of mechanical strain. Leyden jars have usually from ½ to 3 square feet of coated surface. For more powerful charges electric batteries are used.

An *electric battery* consists of a series of Leyden jars, whose inner and outer coatings are respectively connected with each other (fig. 490). They are usually placed in a wooden box lined on the

bottom with tinfoil. This lining is connected with two metal handles in the sides of the box. The inner coatings are connected with each other by metal rods, and the battery is charged by placing the inner coatings in connection with the prime conductor, while the outer coatings are connected with the ground by means of a chain fixed to the handles. A Henley's quadrant electrometer fixed to one jar serves to indicate the potential of the battery. The number of jars is usually four, six, or nine. The larger and more numerous they are, the longer is the time required to charge the battery, but the effects are so much the more powerful.

When a battery is to be discharged the inner and outer coatings are connected by means of a discharging rod, the outside coating being touched first. Great care is required, for with large batteries serious accidents may occur, resulting even in death.

467. **Dissected Leyden jar.**—We have seen that the insulating medium or dielectric (463) in the Leyden jar plays a most important

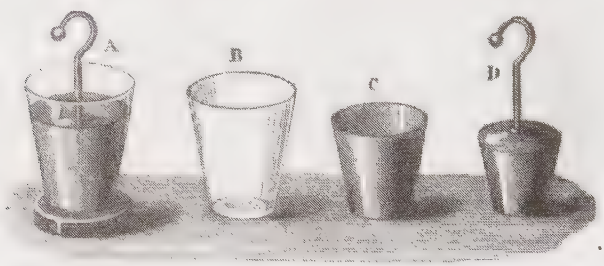


Fig. 491.

part, and it is there, and not on the metallic coatings, that the electricity is stored up. This is illustrated by the experiment of the *dissected Leyden jar*, which consists of a somewhat conical glass vessel, B, with movable coatings of tin, C and D. These separate pieces, placed one in the other, as shown in A (fig. 491), form a complete Leyden jar. After the jar is charged, it is placed on an insulating cake ; the internal coating is first removed by the hand, or, better, by a glass rod, then the glass vessel. The coatings are found to contain little or no electricity, and if they are placed on the table they are restored to the neutral state. Nevertheless,

when the jar is put together again, as represented in the figure at A, a shock may be taken from it almost as strong as if the coatings had not been removed. It is therefore concluded that the coatings principally play the part of conductors, distributing the electricity over the surface of the glass, which thus becomes polarised or strained, and retains this state even when placed on the table with the coatings removed.

The experiment may be conveniently made with an ordinary glass vessel by forming it into a Leyden jar, of which the inside and outside coatings are of mercury. The mercury inside is charged, and then, after the two coatings are mixed, the apparatus is put together again, upon which a discharge may be at once taken. The experiment may also be made by means of an Epinus condenser (461).

468. **Condensing electroscope.**—We shall conclude this account of condensers by describing an application which Volta made

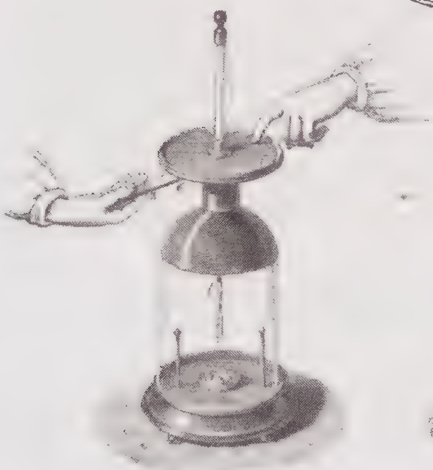


Fig. 492.

Fig. 493.

of the principle of condensation to the ordinary gold-leaf electroscope, by which a far greater degree of delicacy is attained (fig.

492). The rod to which the gold leaves are affixed terminates in a disc instead of in a knob (fig. 452), or instead of the sphere (fig. 453), and there is another disc of the same size provided with an insulating glass handle. Each disc is covered with a layer of insulating shellac varnish (fig. 493).

To render very small differences of potential perceptible by this apparatus, one of the plates, which thus becomes the *collecting plate*, is touched with the body under examination, which is supposed to be at a low but constant potential. The other plate, the *condensing plate*, is put into momentary connection with the ground. The electricity of the body to be tested, being diffused over the collecting plate, acts inductively through the varnish on the neutral electricity of the other plate, attracting the opposite electricity, but repelling that of like kind. The two electricities thus become accumulated on the two plates just as in any other condenser, but there is no divergence of the leaves, for the potential of the body is too low. The finger is now removed, and then the source of electricity, and still there is no divergence ; but if the upper plate is now raised (fig. 493) the capacity of the electroscope is very much diminished, and the charge of electricity remaining constant, it follows that the potential rises, and may rise sufficiently to cause an appreciable divergence of the leaves. For an account of an important experiment by Volta with this electroscope, see art. 489. The delicacy of the apparatus is increased by adapting to the foot of the apparatus two metal rods, which are in conducting communication with the earth, terminating in knobs ; for these knobs, being excited by induction from the gold leaves, react upon them, and, attracting them, increase their divergence.

CHAPTER V

VARIOUS EFFECTS OF ACCUMULATED ELECTRICITY

469. **Effects of the electric discharge.**—The recombination of the two electricities, which constitutes the electric discharge, may be either continuous or sudden : *continuous*, or of the nature of a current, as when the two conductors of an electric machine (449) are joined by a chain or a wire ; and *sudden*, as when the opposite electricities accumulate on the surface of two adjacent conductors until their mutual attraction is strong enough to overcome the intervening resistances, whatever they may be. But the difference between a sudden and a continuous discharge is one of degree, and not of kind, for there is no such thing as an absolute non-conductor, and the very best conductors, the metals, offer an appreciable resistance to the passage of electricity. Still, the difference at the two extremes of the scale is sufficiently great to give rise to a wide range of phenomena.

When the spark produced by the discharge of a Leyden jar is examined by means of a rotating mirror, it forms a band, and on close examination this band is seen to be made up of a number of alternate dark and light spaces, gradually becoming weaker. It

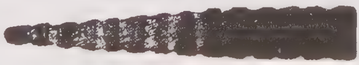


Fig. 494.

thus appears that the discharge of the Leyden jar does not consist in a mere union of the positive and negative electricities, but is made up of a series of oscillating discharges in alternately opposite directions. The shorter and the better conducting is the circuit through which the Leyden jar is discharged, the greater is the number of oscillatory discharges ; conversely, the number of these discharges decreases as the resistance of the circuit through

which the discharge takes place increases. With a very great resistance—for instance, by the interposition of a wet string—the alternating discharge changes into a simple one.

We may compare a dielectric in a state of strain (463), like the glass of a charged Leyden jar, to a narrow steel plate, clamped at one end; if the free end is pulled aside, the plate is in a state of strain, and when this strain is removed the plate comes to rest after making a series of oscillations. These oscillations are *damped* or even prevented when the plate is exposed to a great resistance, by being placed, for instance, in a viscous liquid; so, too, electric discharge becomes continuous when meeting with great resistance.

These oscillatory discharges may be illustrated by means of a simple hydrostatic experiment. Suppose that in the U-tube (fig. 495) is a valve S, by which the two limbs may be separated, and that water is poured in one so that it is at a height L above the level OO, and in the other at a corresponding distance, L′, below the level. When the valve is suddenly opened, the water passes through, and only comes to rest in the position OO after several oscillations. If the valve is only slightly opened, so that great resistance is offered, the water slowly sinks to its level and there are no oscillations; this corresponds to the case in which the electric resistance is very great.

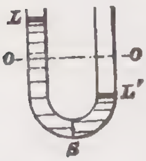


Fig. 495.

The oscillatory nature of the discharge was confirmed by the observations of Paalzow on the luminous phenomena seen in highly rarefied gases when the discharge takes place in them, as well as by the manner in which a magnet affects the phenomena.

470. **Physiological effects.**—The physiological effects are those produced on living beings, or on animals recently deprived of life. In the first case, they consist of a violent excitement which electricity exerts on the sensibility and contractility of the organic tissues through which it passes; and, in the latter, of violent muscular convulsions which resemble a return to life.

The shock from the electric machine has been already noticed. The shock taken from a charged Leyden jar, by grasping the outer coating with one hand and touching the inner with the other, is much more violent, and has a peculiar character. With a small jar the shock is felt in the elbow; with a jar of about a quart capacity it is felt across the chest, and with jars of still larger dimensions in the stomach.

A shock may be given to a large number of persons simultaneously by means of the Leyden jar. For this purpose they must form a chain by joining hands. If then the first touches the outside coating of a charged jar, while the last at the same time touches the knob, all receive a simultaneous shock, the intensity of which depends on the charge and on the number of persons receiving it. Those in the centre of the chain are found to receive a less violent shock than those near the extremities. The Abbé Nollet discharged a Leyden jar through an entire regiment of 1,500 men, all of whom received a violent shock in the arms and shoulders.

With large Leyden jars and batteries the shock is sometimes very dangerous. Priestley killed rats with batteries of 7 square feet coated surface, and cats with a battery of about 4½ square yards coating.

471. **Heating effects.**—Besides being luminous, the electric spark is a source of intense heat. When it passes through inflammable liquids, such as ether or alcohol, it ignites them. An arrangement for effecting this is represented in fig. 496. It is a small glass cup, through the bottom of which passes a metal rod, terminating in a knob and fixed to a metal foot. A quantity of liquid sufficient to cover the knob is placed in the vessel. The outer coating of the jar having been connected with the foot by means of a chain, the spark which passes when the two knobs are brought near each other inflames the liquid. With ether or bisulphide of carbon the experiment succeeds very well, but alcohol requires to be first warmed.

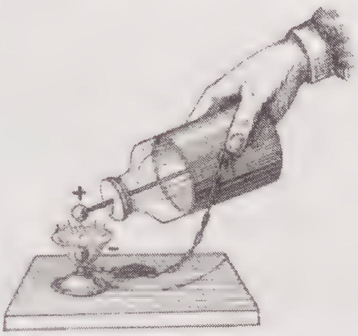


Fig. 496.

The experiment may also be simply made without any special apparatus; a brass rod, connected by a chain with the outer coating of a charged Leyden jar, has a brass knob at one end, which is wrapped round with a few layers of muslin; this is dipped in ether,

and brought near to the knob connected with the inner coating. The spark that ensues at once ignites the ether.

Coal gas may also be ignited by means of the electric spark. A person standing on an insulated stool places one hand on the conductor of a machine, which is then worked, while he presents the other to the jet of gas issuing from a metallic burner. The spark which passes ignites the gas. This experiment may be curiously varied by igniting the gas by means of a piece of ice held in the hand

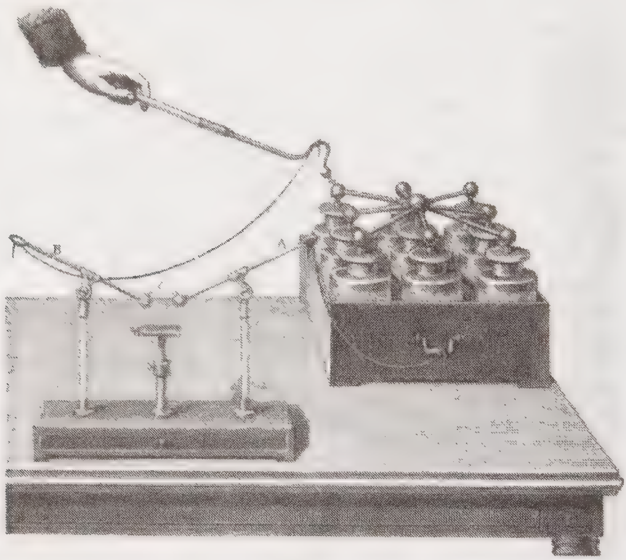


Fig. 497.

A metal wire through which a battery is discharged becomes incandescent, and may be melted or even volatilised, provided the charge be sufficiently powerful.

For this experiment an apparatus is used which is called *Henley's* or *the universal discharger*, for it may be employed in a host of experiments on the electric discharge. It consists (fig. 497) of two brass rods, A and B, each insulated on a glass stem. These rods can slide along hinged joints, so that they can

be adjusted at any distance from each other and inclined in any direction. Between them is a small table support, M, adjustable in height, which is intended to support objects to be submitted to the action of the discharge.

The metal wire which is to be melted is fixed at *i* to two knobs fastened on the rods ; one of these is then connected by means of a chain with the outside of a powerful battery, while the other is brought in contact with the inner coating, either by means of the discharging rod or by a chain attached to a metal rod fixed on a glass handle. The moment the spark passes between the knob and the battery, the wire, if it is fine enough, is melted in incandescent

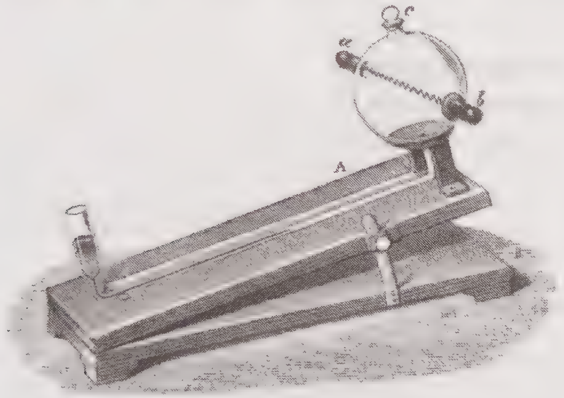


Fig. 498.

globules, and is even volatilised—that is, converted into vapour which disappears in the atmosphere. If the wire is thicker, it simply becomes red-hot, but does not melt ; and if still larger, it is merely heated without becoming luminous.

The laws of this heating effect have been investigated by the apparatus illustrated in fig. 498, known as the *electric thermometer*. It consists of a glass bulb closed by a stopper, *c*, and attached to a capillary tube, which is bent twice and terminates in an enlargement ; this contains coloured liquid. The whole apparatus is fixed on a hinged support, A, which works on the base, B, so that it can be inclined and fixed at any given angle. Before the experiment is made the stopper, *c*, is opened to equalise the

pressure on the two ends of the liquid. Between the terminals, *a* and *b*, a fine platinum wire spiral is stretched. When a Leyden jar is discharged through *ab*, the wire becomes heated, expands the air in the bulb, and the expansion is indicated by the motion of the liquid along the graduated stem of the thermometer. In this way it was found that the heat in the wire is proportional to the square of the quantity of electricity, and inversely proportional to the capacity of the Leyden jar.

Fig. 499 represents the marks left on a piece of glass by a narrow strip of tinfoil fused by the discharge of a Leyden battery.

When an electric discharge is sent through gunpowder placed on the table of a Henley's discharger, the powder is not ignited, but is scattered in all directions. But if a wet string is interposed in the circuit, a spark passes which ignites the powder. This arises from the retardation which electricity experiences in traversing a semi-conductor, such as a wet string; for the heating effect is proportional to the duration of the discharge.

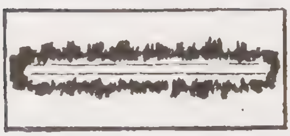


Fig. 499.

472. **Electric portraits.**—The volatilisation of metals by the electric discharge is applied to make what are called *electric portraits*. For this purpose a thin card is taken of the shape *abm* (fig. 500), and the design to be copied is cut out of the central part, *c*, the terminal parts, *a* and *b*, being covered with tinfoil. A leaf of gold is then placed upon the design, care being taken that it touches both the pieces of tinfoil, *a* and *b*. The lateral portion of

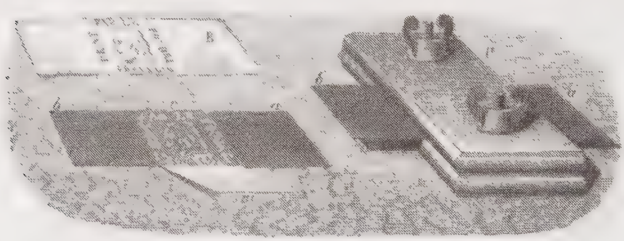


Fig. 500.

the card, *m*, is then bent over, the card placed on a silk ribbon, and the whole pressed in a frame, P. When the discharge is passed from *a* to *b*, the tinfoil, being relatively thick, is not melted; but the gold, which is very thin, is volatilised, and forms on the ribbon through the pattern a brown coating, which reproduces all the details as seen in R.

473. **Mechanical effects.**—The mechanical effects are the violent lacerations, fractures, and sudden expansions which ensue when a powerful discharge is passed through a badly conducting substance. Glass is perforated, wood and stones are fractured, and gases and liquids are violently disturbed. The mechanical

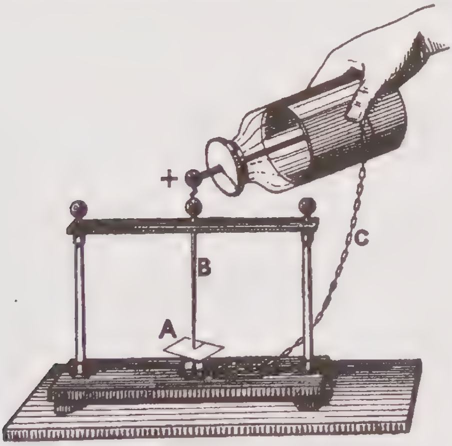


Fig. 501.

effects of electricity may be demonstrated by a variety of experiments. The body to be submitted to experiment is placed on the table, M (fig. 497), in contact with the two knobs which terminate the rods A and B, so that they cannot receive the discharge without transmitting it through the object on the table. Thus, for instance, if a piece of wood is placed so as to be struck in the direction of the fibres, it is smashed into pieces the moment the discharge passes.

Fig. 501 represents an arrangement for perforating a piece of glass or card. It consists of two glass columns, with a horizontal cross-piece, in which is a pointed conductor. The piece of glass

is placed on an insulating glass support, in which is placed a second conductor terminating also in a point, which is connected with the outside of the battery, while the knob of the inner coating is brought near the other knob. When the discharge passes between the two conductors, the glass is penetrated. The experiment only succeeds with a single jar when the glass is very thin ; otherwise a battery must be used.

When the discharge takes place through a piece of cardboard between two points exactly opposite each other, the line of perforation is quite straight ; but it not exactly opposite, a slight hole is seen near the negative point. This phenomenon, which is known as *Lullin's experiment*, is probably connected with the fact that electricity is discharged more readily from a negatively than from a positively charged point (455).

Fig. 502.

If the discharge be passed between the knobs *a* and *b* (fig. 502) in a glass tube containing water, the explosion is so violent that the tube is smashed.

474. **Chemical effects.**—The chemical effects are the decompositions and recombinations effected by the passage of the electric discharge. An instance of chemical combination brought about by the electric spark has been already given in the formation of water, shown in fig. 483. Priestley found that when a series of electric sparks was passed through moist air contained in a bent tube over mercury (fig. 503), its volume diminished, and blue litmus introduced into the vessel was reddened. This, Cavendish found, was due to the formation of nitric acid.

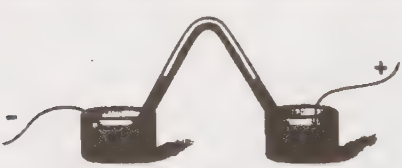


Fig. 503.

Water may conversely be decomposed by electric sparks. This is best effected by means of what are called *Wollaston's points*, which consist of fine platinum wires fused into capillary glass tubes, and filed away so that only the section of the wire is presented to the liquid. If two such points placed in water (fig. 504) are connected, by means of mercury in the tubes and the wires *d*, with the electrodes of a Wimshurst machine, or, in the case of a frictional machine, one with the prime conductor and the

other with earth, there being in either case a spark-gap of about a millimetre, it will be found that minute bubbles of oxygen gas are given off at the point at which the positive electricity enters, or the positive pole, while about twice the quantity of hydrogen gas is given off at the negative pole. If the experiment is made with solution of copper sulphate, oxygen is still given off at the positive pole, while the negative becomes coated with metallic copper.

Decomposition of salts may also be easily shown by Faraday's experiment (fig. 505), which consists in placing discs of blotting-paper, B and D, soaked with solution of the salt in question, on a table A. Connection is established between the discs, and with the prime conductor, C, on the one hand, and the earth on the

Fig. 504.

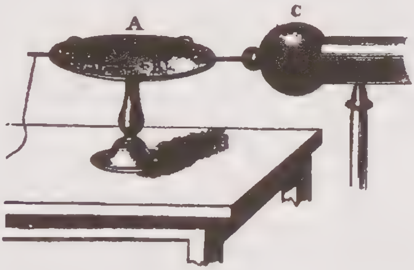


Fig. 505.

other, by means of fine platinum wire. If the solution is one of a neutral salt—sodium sulphate, for example—decomposition takes place when the machine is worked, and free acid, recognisable by its action on litmus, is liberated at B, while D indicates the presence of free alkali.

Among the chemical effects must be enumerated the formation of *ozone*, which is recognised by its peculiar odour and by its chemical properties, which are like those of oxygen, but far more energetic. The odour is perceived when an electric machine is at work and electricity issues through a series of points from a conductor into the air. It has been ascertained to be an allotropic modification of oxygen, which has properties the same in kind as those of oxygen, though much more powerful in degree.

475. **Magnetic effects.**—By the discharge of a large Leyden jar or battery, a steel wire may be magnetised if it is laid at right

angles to the conducting wire through which the discharge is passed, either in contact with the wire or at some slight distance. And even with less powerful discharges a steel bar or needle may be magnetised by being placed inside a spiral of fine insulated copper wire (fig. 506). When the discharge is passed through this wire the needle becomes magnetised. If the wire is coiled round the needle in the same direction as that in which the hands of a watch move, the south pole is at that end at which the positive electricity enters. If, on the contrary, the wire is coiled in the opposite direction to the hands of a watch, the north pole is at the end at which the positive electricity enters.

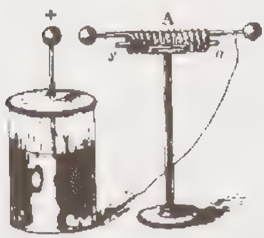


Fig. 506.

The polarity of the needle is generally as stated above; it is, however, sometimes found that the passage of an electric discharge through the spiral produces very little magnetic effect on the needle, and occasionally the polarity is opposite to what we should expect. These anomalies are due to the oscillatory character of the discharge of a Leyden jar (469). Uniform results are obtained when a wet string is included in the circuit.

The magnetic action may also be illustrated by discharging a charged condenser through a galvanometer (521), which must have a long coil of well-insulated wire. A momentary deflection, or *throw*, of the needle is produced, which is a measure of the quantity of electricity with which the condenser is charged. If the terminals of the galvanometer are connected with the electrodes of a Wimshurst machine in action, a steady deflection of the needle is obtained.

476. **Inductive effects of the Leyden discharge.**—The discharge of a Leyden jar can induce a discharge in a separate conductor, as may be illustrated by the apparatus represented in fig. 507. B and C are flat coils of insulated wire fastened on glass plates. One end of the wire on B is connected with the discharging rod, and the other with the outside coating of a charged Leyden jar. When the spark passes, electricity traversing the wire on B acts by induction on the wire on C, and produces a momentary current in this wire. A person holding two brass handles, h_1 and h_2, connected with the two ends of the wire on C, receives a shock, the strength

of which is greater in proportion as B and C are nearer. A fragment of gun-cotton placed between h_1 and h_2 will be ignited by the discharge of the jar ; or, if h_1 and h_2 are connected by a magnetising spiral, a needle placed inside it will be magnetised by the discharge.

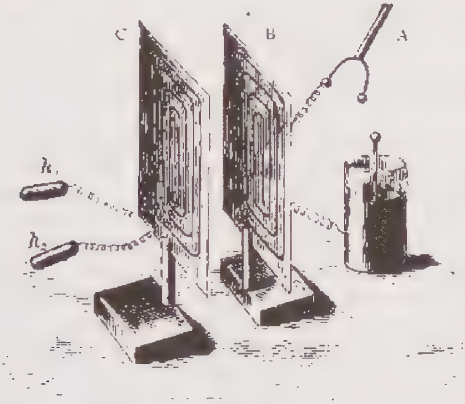


Fig. 507.

The experiment may also be made by simply twisting together two lengths of a few feet of gutta-percha-covered copper wire. The end of one length being held in the hand, an electric discharge is passed through the other length.

CHAPTER VI

ATMOSPHERIC ELECTRICITY. THUNDER AND LIGHTNING

477. **Thunder and lightning the effects of electricity.**—The first physicists who observed the ramified motion of the electric spark compared it to the gleam of lightning, and its crackling to the sound of thunder. But Franklin, by the aid of powerful electric batteries, was the first to establish a complete parallelism between lightning and electricity; and in a memoir published in 1749 he pointed out the experiments necessary to attract electricity from the clouds by means of pointed rods. The electric fluid, said he, in concluding his memoir, is attracted by points; we know not whether lightning is endowed with the same property; but since electricity and lightning agree in all other respects it is probable they will not differ in this—and *the experiment should be made.* The experiment was tried by Dalibard in France; and Franklin, pending the erection of a pointed rod on a spire in Philadelphia, had the happy idea of flying a kite, provided with a metal point, which could reach the higher regions of the atmosphere. In June 1752, during stormy weather, he flew the kite in a field near Philadelphia. The kite was flown with ordinary packthread, at the end of which Franklin attached a key, and to the key a silk cord, in order to insulate the apparatus; he then fixed the silk cord to a tree, and having presented his hand to the key at first he obtained no spark. He was beginning to despair of success, when, rain having fallen, the cord became a good conductor, and a spark passed. Franklin, in his letters, describes his emotion on witnessing the success of the experiment as being so great that he could not refrain from tears.

Franklin, who had discovered the property of points (455), but who did not understand its explanation, imagined that the kite withdrew its electricity from the clouds; it is, in fact, a simple case of induction, and depends on the inductive action which the thunder-cloud exerts upon the kite and the cord.

478. **Atmospheric electricity.**—In order to ascertain the presence of electricity in the atmosphere, many forms of apparatus have been used. To observe the electricity in fine weather, an electrometer may be used, as devised by Saussure for this kind of investigation. It is an electroscope similar to that already described, but the rod to which the gold leaves are fixed is surmounted by a conductor two feet in length, and terminating either in a knob or a point (fig. 508). To protect the apparatus against rain, it is covered with a metal shield four inches in diameter. The glass case is square, and a divided scale on its inside face indicates the divergence of the gold leaves.

Fig. 508.

To ascertain the electric state of the atmosphere, Saussure also used a copper ball, which he projected vertically with his hand. This ball was fixed to one end of a metal wire, the other end of which was attached to a ring, which could glide along the conductor of the electrometer. From the divergence of the gold leaves the electric condition of the air at the height which the ball had attained could be determined. Becquerel, in experiments made on Mont St. Bernard, improved Saussure's apparatus by substituting for the ball an arrow, which was projected into the atmosphere by means of a bow. A gilt silk thread, eighty-eight yards long, was fixed with one end to the arrow, while the other was attached to the stem of an electroscope.

Volta charged a small Leyden jar with the electricity in the air by an arrangement represented in fig. 509. An ordinary rod is held in the hand, provided at one end with a brass ferrule in which fits a glass rod ; this in turn is provided with a ferrule in which is fixed a pointed metal rod, E. At the end of this is a cotton wick, G, soaked in spirits of wine. A wire, H, connects the wick to the inner coating of a small Leyden jar, the outer coating of which is held in the hand. Instead of the Leyden jar a small electroscope may be used with this arrangement.

Sometimes also kites are used, provided with a point, and connected by means of a gilt cord with an electrometer. Captive balloons are likewise similarly used.

A good collector of atmospheric electricity consists of a fishing-rod with an insulating handle, which projects from an upper window. At the end of the rod is a bit of lighted tinder, held in metal forceps, the smoke of which, being an excellent conductor, conveys the electricity of the air down an insulated wire attached to the rod. A sponge moistened with alcohol, and set on fire, is also an excellent conductor.

Fig. 509.

479. **Ordinary electricity of the atmosphere.**—By means of the various apparatus which have been described, it has been found that the presence of electricity in the atmosphere is not confined to stormy weather, but that the atmosphere always contains electricity—generally positive, though occasionally negative. In other words, the electric potential at any point in the atmosphere is generally above, and only occasionally below, that of the earth; so that if the point in question is connected by a wire with the earth, there is generally a flow of positive electricity down the wire. When the sky is cloudless, the potential is always positive, but it varies in amount with the height of the locality and with the time of day. The potential is greatest in the highest and most isolated places. No trace of electricity is found in houses, streets, or under trees; in towns, positive electricity is most perceptible in large open spaces, on quays, or on bridges. In all cases, positive electricity is only found at a certain height above the ground. On flat land it only becomes perceptible at a height of five feet; above that point it increases according to a law which is not established, but which seems to be affected by the hygrometric state of the air.

When the sky is clouded, the electricity is sometimes positive and sometimes negative. It often happens that the electricity changes its sign several times in the course of the day, owing to the

passage of an electrified cloud. During storms, and when it rains or snows, the atmosphere may be positively electrified one day, and negatively the next, and the numbers of the two sets of days are virtually equal. The electric potential at a given position above the ground is relatively high during fog, and is nearly always positive in fine weather. It increases in general with the density of the fog.

The electricity of the ground was found by Peltier to be always negative, but to different extents, according to the hygrometric state and temperature of the air.

Many hypotheses have been propounded to explain the origin of atmospheric electricity. Some have ascribed it to the friction

Fig. 510.

of the air against the ground, some to the growth of plants, or to the evaporation of water. Several causes may, in fact, concur in producing the phenomena, and it must be admitted that at present we are unable to give any satisfactory explanation. The fact that the most powerful atmospheric phenomena are accompanied by enormous downpours of rain and hail seems to indicate a connection between the excitation of electricity and the condensation of aqueous vapour, which has not, however, been put on an experimental basis. Thus, in volcanic outbursts, large masses of aqueous vapour ascend and condense at a height, forming a massive cloud, which, after sending forth lightning-flashes accompanied by thunder, is resolved into rain.

480. **Lightning.**—This, as is well known, is the dazzling light emitted by the electric spark when it shoots from clouds charged with electricity. In the lower regions of the atmosphere the light

Fig. 511.

Fig. 512.

is white, but in the higher regions, where the air is more rarefied, it takes a violet tint, as does the spark of the electric machine in a rarefied medium (456).

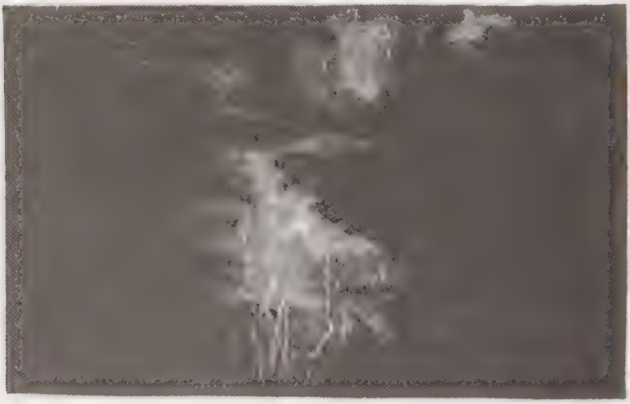


Fig. 513.

The extremely sensitive photographic dry plates now made (404) have put into the hands of meteorologists a powerful means of studying the exact forms of lightning-flashes. Figs. 510 to 513 are reproductions of photographs of lightning taken at various times

and places, selected by a Committee of the Royal Meteorological Society, as representing actual typical forms.

Stream lightning (fig. 510) is rather a rare form ; it consists of a plain, broad, rather smooth streak of light. *Sinuous* lightning (fig. 513) is the commonest type : the flash maintains some general direction, but the line is sinuous, bending from side to side in a very irregular manner. In *ramified* lightning (fig. 511) part of the flash appears to branch off from the main streak, like the fibres from the root of a tree. In *meandering* lightning, as in fig. 512, the flash appears to meander about without any definite course, and forms small irregular loops. Occasionally a series of bright beads appears in the general wide streak of lightning. Sometimes these beads seem to coincide with bends in the meandering type, but they often appear without any evident looping of the flash.

A lightning-flash between a cloud and the earth may be regarded as the discharge of a condenser whose coatings are the charged clouds and the earth, the intervening air being the dielectric. And as with a Leyden jar the discharge is ordinarily oscillatory in character (469), so is it also in the case of a lightning-flash. The discharge oscillates to and fro between the cloud and the ground, the whole series of alternations taking place in a minute fraction of a second and appearing to the eye as a single flash. Only in the case of meandering lightning (fig. 512) is the discharge probably non-oscillatory.

Besides these types there are also the flashes which, instead of being linear, like the preceding, fill the entire horizon without having any distinct shape. This kind, which is most frequent, appears to be produced in the cloud itself, and to illuminate the mass. Another kind is called *heat* or *sheet* or *summer* lightning, because it illuminates the summer nights without the presence of any clouds above the horizon, and without producing any sound. The most probable of the many hypotheses which have been proposed to account for its origin is that which supposes it to consist of ordinary lightning-flashes, which strike across the clouds at such distances that the rolling of thunder is so enfeebled as not to affect the ear of the observer.

Thus, Luke Howard observed at Tottenham, while the sky was perfectly clear, abundant sheet lightning in a south-easterly direction, and afterwards learned that there had been at the same time a violent thunderstorm between Dunkirk and Calais, a distance

of over 100 miles. Lightning is visible at a distance of 150 miles, while thunder is not heard at a greater distance than 17 miles.

There is, further, the rarer phenomenon of lightning-flashes which appear in the form of globes of fire, known also as *fireballs*. These, which are sometimes visible for as long as ten seconds, descend from the clouds to the earth with such slowness that the eye can follow them. They often rebound on reaching the ground; at other times they burst and explode with a noise like that of the report of many cannon. This is sometimes known as *globe* lightning or *thunderbolts*, and its existence might even be doubted if M. Planté had not obtained, by means of batteries of very high potential, discharges which at times took the form of a luminous sphere.

The duration of the light of the first three kinds does not amount to the one hundred thousandth of a second, as has been determined by Wheatstone by means of a rotating wheel, which was turned so rapidly that the spokes were invisible (378); on illuminating it by a lightning-flash, its duration was so short that, whatever the velocity of rotation of the wheel, it appeared quite stationary—that is, its displacement was not perceptible during the time the lightning existed.

The length of a flash of lightning may be ascertained by determining its angular extent, and the time which elapses between its appearance and the subsequent thunder. This time in seconds, multiplied by the velocity of sound in feet per second, gives the radius in feet of the arc traversed.

The light produced by a lightning-flash must be comparable to that of the sun in brightness, though it does not appear to us brighter than ordinary moonlight. But considering its excessively brief duration, and that the full effect of any light on the eye is only produced when its duration is at least the tenth of a second, it follows that a landscape continuously illuminated by the lightning-flash would appear 100,000 times as bright as it actually appears to us during the flash.

481. **Thunder.**—*Thunder* is a violent report which succeeds lightning in stormy weather; it is the crack of the ordinary electric spark on a large scale. The lightning and the thunder are always simultaneous, but an interval of several seconds is generally observed between the perception of these two phenomena, which arises from the fact that sound only travels at the rate of about

1,100 feet in a second (175), while the passage of light is almost instantaneous. Hence an observer will only hear the noise of thunder five or six seconds, for instance, after the lightning, according as the distance of the thunder-cloud is five or six times 1,100 feet. The noise of thunder arises from the disturbance which the electric discharge produces in the air. Near the place where the lightning strikes, the sound is hard and of short duration. At a greater distance a series of reports are heard in rapid succession. At a still greater distance the noise, feeble at the commencement, changes into a prolonged rolling sound of varying intensity. Some attribute the noise of the rolling of thunder to the reflections of sound from the ground and from hills, clouds, and buildings, which do not all reach the ear at the same time. Others have considered the lightning, not as a single discharge, but as a series of discharges, each of which gives rise to a particular sound; but as these partial discharges proceed from points at different distances, and from zones of unequal density, it follows not only that they reach the ear of the observer successively, but that they bring sounds of unequal intensity, which occasion the duration and inequality of the rolling. The phenomenon has finally been ascribed to the zigzags of lightning themselves, assuming that the air at each salient angle is at its greatest compression, which would produce the unequal intensity of the sound. One observer gives the duration of thunder as varying from two to eighty seconds.

Thunder-clouds are usually flat at the bottom, while above are more or less dense masses of cloud piled up in peaks and hillocks. In reflected light such clouds are brilliantly white, but from their great density they transmit but little light, and hence when they are between us and the sun they seem dark grey or black. Each such cloud is due to an ascending current of air, which shows itself by the condensation of the moisture in the air. When the cloud is high enough, the column begins to spread out in the above forms, and is ultimately resolved into cirrus. Lightning and thunder are then not far off. Thunder-clouds are usually at a height of 3,000 to 4,000 feet, though they have been known to be as low as from 700 to 1,000 feet.

Mohn observed that the average rate at which thunderstorms travel in Norway is about twenty-four miles an hour, and mostly from south-west to north-east.

482. **Effects of lightning.**—The lightning discharge is the electric discharge which strikes between a thunder-cloud and the

earth. The latter, by the induction from the electricity of the cloud, becomes charged with contrary electricity; the electrified cloud and the earth are in a condition like the two coatings of a Leyden jar (481), and when the tendency of the two electricities to combine exceeds the resistance of the air the spark passes, which is often expressed by saying that a 'thunderbolt has fallen.' Lightning in general strikes from above, but *ascending lightning* is also sometimes observed; possibly this is the case when, the clouds being negatively, the earth is positively electrified, for experiments show that at the ordinary atmospheric pressure positive electricity passes through the atmosphere more easily than negative electricity.

We should expect the lightning-flash to take place between the charged cloud and the nearest and best conducting objects, and in fact trees, elevated buildings, metals, are more particularly struck by the discharge; but many exceptions to this general principle are on record. Trees are good conductors, from the sap they contain; hence it is imprudent to stand under or very near trees or shrubs during a thunderstorm.

Curious effects are observed in the action of lightning on trees. Sometimes they are partially or entirely deprived of their bark; sometimes the wood is split into long thin laths, or cut up in bundles of fibres like a broom. Franklin ascribed this phenomenon to the sudden evaporation of the sap contained in the wood. Lightning often runs on the outside in a spiral line, or rotates about their axes on the stems of trees or posts.

Fig. 514.

The effects of lightning are very varied, and of the same kind as those of electric batteries (466), but of far greater intensity. The lightning discharge kills men and animals, inflames combustible matter, melts metals, breaks bad conductors in pieces. When it penetrates the ground it melts the siliceous substances on its path, and thus often produces, in the direction of the discharge, those remarkable vitrified tubes called *fulgurites* (fig. 514), some of which are twelve yards in length. They are as much as two inches wide at the top, and their branches run out to fine points. When it strikes bars of

iron, it magnetises them, and it often reverses the poles of compass-needles.

After the passage of lightning, a peculiar odour is sometimes produced, like that perceived in a room in which an electric machine is being worked. This odour is due to the formation of ozone (474). Rain-water, too, collected after a thunderstorm contains on the average more nitric acid than under ordinary circumstances. The production of this acid is one of the effects of the electric discharge through air (474).

An electrified cloud forms, with the earth below, a condenser, the intervening mass of air being the dielectric. This mass of air is therefore in a state of strain, like the dielectric in a Leyden jar, and it is to this state of strain which precedes the actual discharge, rather than to the discharge itself, that is due the production of ozone or of nitric acid.

Heated air conducts better than cold air, probably only owing to its lesser density. Hence it is said that large numbers of animals, such as flocks of sheep, are often killed by a single discharge, as they crowd together in a storm, and a column of warm air rises from the group.

Many persons have an undue fear of the effects of the lightning discharge. This fear would be diminished if we remembered the very small number of persons who are really killed by lightning. Arago estimated the number for France at twenty in a year—that is, one victim for two million inhabitants—which is a far less proportion than that of many other accidents which do not excite nearly so much fear. The danger of possible death from a lightning discharge is far less than that from a railway accident.

The frequency of thunderstorms varies greatly in different countries. In Central Europe they are more frequent than in the west, especially in those places bordering on the sea. Thus, while there are from 5 to 10 in a year in the latter, in Germany there are 30, and in Italy 40 in the year. In London they vary from 5 to 13, the average being 8·5, while in Paris the average is 14. In tropical countries they are far more frequent. They mostly occur in summer, but where the rainfall is greatest in winter, as at Bergen, they are more frequent at that time of the year.

483. **Return shock.**—This is a violent and sometimes fatal shock which men and animals experience, even when at a great distance from the place where the lightning discharge passes. It is caused by the inductive action which the thunder-cloud exerts

on bodies placed within the sphere of its activity. These bodies are then, like the earth, charged with the opposite electricity to that of the cloud; but when the latter is discharged by the recombination of its electricity with that of the earth—thus, when the discharge strikes a steeple—the induction ceases, and, the bodies reverting rapidly from the electric state to the neutral state, the concussion in question is produced—the *return shock*. A more gradual decomposition and reunion of the electricity produces no visible effects; yet it is not improbable that such disturbances of the electric equilibrium are perceived by nervous persons.

The return shock is always less violent than the direct one; there is no instance of its having produced any direct apparent inflammation, yet plenty of cases in which it has killed both men and animals; in such cases no broken limbs, wounds, or burns are observed.

The return shock may be imitated by placing a gold-leaf electroscope, the knob of which is connected by a wire with the ground, near the prime conductor of a powerful electric machine in action; the leaves diverge, but at each spark taken from the machine they suddenly collapse.

484. **Lightning-conductor.**—A lightning-conductor is a metallic rod attached to the side of a building, its upper end being carried above the highest point of the roof, and its lower end embedded in the ground. It was devised by Franklin in 1755 for the purpose of protecting buildings from the effects of lightning. It is usually made of iron or copper, in the form of rod or stranded wire or flat band, and terminates at the top in a point or series of points (fig. 515). The conductor is usually led into a well, and to connect it better with the soil it ends in two or three branches, or is connected with a large plate of metal called an *earth-plate*. If there is no well close at hand, a hole is dug in the soil to a depth of six or seven feet, or to a depth at which the ground is moist, and, the plate of the conductor having been introduced, the earth is strongly rammed against it. Good connection with the earth, or what is called *good earth*, is of great importance with lightning-conductors.

As the action of a lightning-conductor depends on induction and the property of points, Franklin, as soon as he had established the identity of lightning and electricity, assumed that lightning-conductors withdrew electricity from the clouds; the converse is the case. When a storm-cloud, positively electrified, for instance, rises in the atmosphere, it acts inductively on the

earth, giving rise to a negative charge, which accumulates in bodies placed on the surface of the soil the more abundantly as these bodies are at a greater height. The electrostatic pressure is then greatest on the highest bodies, those, therefore, which are most exposed to the electric discharge ; but if these bodies are provided with metal points, like the rods of conductors, the negative electricity, withdrawn from the ground by the influence of the cloud, flows into the atmosphere, and neutralises the positive electricity of the cloud. Hence, not only does a lightning-conductor tend to

Fig. 515.

prevent the accumulation of electricity on the surface of the earth, but it also tends to restore the clouds to their natural state, both which actions concur in preventing lightning-discharges. This is, indeed, the manner in which the action of lightning-conductors comes most frequently into play, though not always. The disengagement of electricity is, however, sometimes so abundant that the lightning-conductor is inadequate to discharge the electricity, and the lightning strikes ; but the conductor receives the discharge, in consequence of its greater conductivity, and the building is preserved.

A lightning-conductor should satisfy the following conditions: 1. The rod ought to be so large as not to be melted if the discharge passes. 2. It ought to terminate in a point or in several points, to give readier issue to the electricity disengaged by induction from the ground. 3. The conductor must be continuous from the point to the ground, and the connection between the rod and the ground must be as intimate as possible. 4. If the building which is provided with a lightning-conductor contains metallic surfaces of any extent, such as zinc roofs, metal gutters, or ironwork, these ought to be connected with the conductor. If the last two conditions are not fulfilled, there is a great danger of *lateral discharges*—that is to say, that the discharge takes place between the conductor and the edifice, and then it increases the danger.

A very simple, and at the same time efficient, lightning-conductor may be easily fitted to any ordinary dwelling-house. It consists of a length of iron tubing an inch or more in diameter, which at the bottom is connected with the drains of the house, and projects above the highest point of the building, and which may, if desired, have a pointed rod attached to the top.

The system of protection against lightning discharges introduced by Melsens is based on the principle that when any body is placed inside a sort of cage, formed of a network of metal wires in connection with the ground (439), the body is not acted on by electrified bodies placed outside the cage.

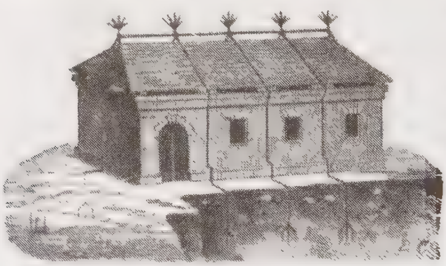


Fig. 516.

This is effected by placing on the roof and the outside of the building iron wires, which are connected with each other, so as to form a network which is connected with the earth in many points (fig. 516). At the principal intersections of the conductors, and particularly on the ridge, are placed brushes formed of copper wire, through which the electricity escapes. A similar arrangement is used for the protection of powder magazines.

485. **Aurora borealis.**—The *aurora borealis*, or northern

light, or more properly *polar aurora*, is a remarkable luminous phenomenon which is frequently seen in the atmosphere at the two terrestrial poles, but more especially at the north pole (fig. 517). At the close of the day an indistinct light appears on the horizon in the direction, not of the geographical, but of the magnetic meridian. This luminosity gradually changes into a regular arc of a pale yellow, with its concave side turned towards the earth. Finally, the rays burst all over the horizon, passing successively from yellow to deep green, and to the most brilliant purple, and forming a portion of an immense luminous cupola.

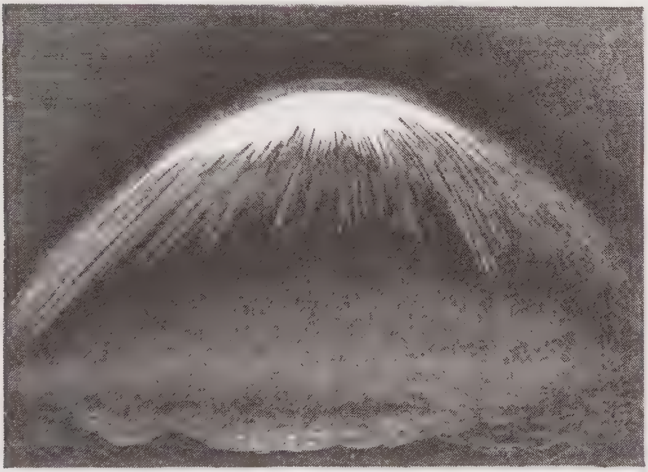


Fig. 517.

When the luminous arc is formed, it often remains visible for some hours; then the lustre diminishes, the colours disappear, and this brilliant phenomenon gradually vanishes, or is suddenly extinguished.

As the aurora shares the rotatory motion of the earth, it must be regarded as an atmospheric phenomenon. The constant direction of its arc as regards the magnetic meridian, and its action on the magnetic needle (420), suggest that it ought to be attributed to electric currents in the higher regions of the atmosphere. This

hypothesis is confirmed by the circumstance that during the prevalence of the aurora borealis electric telegraph lines are spontaneously affected in a powerful but irregular manner; magnetic needles are deflected, the armatures of magnets attracted, and bells rung. This interference is at times so serious, especially in northern countries, that it is necessary to suspend the ordinary transmission of telegraphic messages. The discharges are, in fact, occasionally so steady and continuous as to form a true current of electricity, and cases are known in which the telegraphic wires have been detached from the battery, and the discharge has been used instead.

Attempts to deduce the height of the aurora borealis have not led to consistent results. Professor Lemström, director of the Finnish polar station, observed such phenomena below the clouds and on the tops of mountains. He even succeeded in artificially reproducing such phenomena on the tops of two mountains of Northern Finland, the heights of which were 2,620 feet and 3,620 feet, by means of electric action.

De la Rive ascribed auroræ boreales to electric discharges which take place in polar regions between the positive electricity of the atmosphere and the negative electricity of the terrestrial globe; and in chapter xii. an experiment will be described which De la Rive devised in support of this hypothesis (559).

486. **St. Elmo's fire.**—This name is given by sailors to the luminous brushes or stars which sometimes appear at the tops of masts and yards of vessels, the tops of trees, of church steeples, of flagstaffs, and of weather vanes, and which are often accompanied by a crackling sound, resembling that heard when sparks are taken from electric machines.

Similar effects are not unfrequently met with in the Alps on travellers' umbrellas and alpenstocks, and even on the hair and the clothes. They are also sometimes seen at night, and, in stormy weather, on the points of lightning-conductors.

These luminous effects were known to the ancients. Pliny speaks of the fiery stars seen on the ends of soldiers' lances. When they were two in number they were compared to Castor and Pollux, and that was a favourable presage; if only one appeared, it was likened to their sister Helena, which was considered to be a bad omen.

St. Elmo's fire is a simple case of induction. The atmospheric electricity acting on conductors decomposes the neutral electricity,

attracting the contrary electricity, which from the power of points, being liberated at the extremities of the masts, or by the metal of the lances, gives rise to the luminous brush. The same effect is observed from a metal point on the conductor of the electric machine, when it is made to work in darkness.

487. **Atmospheric electricity on the Pyramids.**—Some curious observations were made by Siemens on the summit of the Cheops pyramid during the prevalence of the *kamsin* (309). On stretching his finger out a peculiar hissing sound was heard, and at the same time a prickly sensation was felt. On holding in one hand a filled champagne bottle, the cork of which was coated with tinfoil, the same sound was heard, and sparks continually passed from the label to the hand which held the flask, and when Siemens touched the top with the other hand he experienced a powerful shock.

In this case the liquid which was in conducting communication with the cork formed the inner coating of a Leyden jar, the outer coating of which was formed by the label and by the hand.

When the jar was improved by coating it with moistened paper, it gave such powerful discharges, with a striking distance of half an inch, that an Arab who held Siemens's hand was thrown to the ground as if struck by lightning when Siemens presented the bottle to his nose.

CHAPTER VII

ELECTRICITY DUE TO CHEMICAL ACTION. VOLTAIC BATTERY

488. **Galvani's experiment.**—We have already seen that the two most powerful sources of electricity are friction and chemical action. Having described the former, we are now to be concerned with the latter. Yet it may be premised that we are not concerned here with a new kind of electricity, but only with another method for its production yielding far larger quantities than can be obtained by friction, and leading to the most remarkable effects.

To Galvani, professor of anatomy in Bologna, is due the discovery in 1790 of these new electric phenomena, to which he was led by a casual observation. It is said that a dead frog was accidentally suspended by a copper hook to the iron railings of a balcony; it was observed to be violently contracted whenever the legs of the animal came into contact with the iron bars.

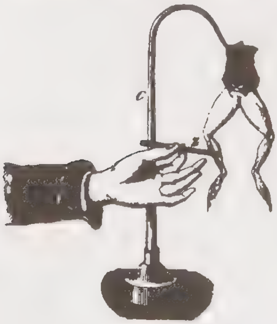


Fig. 518.

Galvani's observation may be reproduced in the following manner: the legs of a recently killed frog are prepared, and suspended to a copper hook, which passes between the vertebral column and the nerve filaments on each side of it. If then the copper support and the legs are momentarily connected by a plate of zinc, a smart contraction of the muscles ensues at each contact (fig. 518). Galvani had some time before observed that the electricity of machines produced in dead frogs analogous contractions, and he attributed the phenomena first described to an electricity inherent in the animal. He assumed that this electricity, which he called *vital fluid*, passed from the nerves to the muscles by the metallic arc, and was thus

the cause of contraction. This theory met with great support, especially among physiologists, but it was not without opponents. The most considerable of these was Alexander Volta, professor of physics in Pavia.

489. **Volta's fundamental experiment.**—Galvani's attention had been exclusively devoted to the nerves and muscles of the frog, Volta's was directed upon the connecting metal. Resting on the observation, which Galvani had also made, that the contraction is more energetic when the connecting arc is composed of two metals than when there is only one, Volta attributed to the metals the active part in the phenomenon of contraction. He assumed that the disengagement of electricity was due to their contact, and that the animal parts only officiated as conductors, and at the same time as a very sensitive electroscope.

By means of the then recently invented condensing electroscope, Volta devised several modes of showing the disengagement of electricity on the contact of metals, of which the following is the easiest to perform :—

The moistened finger being placed on the upper plate of a condensing electroscope (fig. 492), the lower plate is touched with a plate of copper, *c*, soldered to a plate of zinc, *z*, which is held in the other hand. On breaking the connection and lifting the upper plate (fig. 493), the gold leaves slightly diverge, and, as may be proved, with negative electricity. Hence, when zinc and copper are soldered together, the copper is charged with negative electricity, and the zinc with positive. The electricity could not be due either to friction or pressure ; for if the condenser plate, which is of copper, is touched with the zinc plate, *z*, the copper plate to which it is soldered being held in the hand, no trace of electricity is observed.

A memorable controversy arose between Galvani and Volta. The latter was led to give greater extension to his contact theory, and propounded the principle that *when two heterogeneous substances are placed in contact, one of them always assumes the positive and the other the negative electric condition.* In this form Volta's theory obtained the assent of the principal philosophers of his time.

490. **Voltaic pile.**—Reasoning from this theory of contact, Volta was led in 1800 to the invention of the marvellously simple apparatus which immortalised him and which is known to this day as the *Voltaic pile.* Wishing to multiply the points of

contact, and to collect the electricities produced by each, Volta arranged, as represented in fig. 519, a disc of zinc, a disc of copper, then a round piece of cloth moistened with acidulated water, then again a disc of zinc, a disc of copper, a piece of cloth, and so forth, care being taken always to preserve the same order. What was to be expected from such a combination? Arago says: 'I do not hesitate to assert that this mass, so inert in appearance, this pile of so many couples of metal separated by a little liquid, is, as regards the singularity of its effects, the most remarkable instrument which has ever been invented, not even excepting the telescope and the steam-engine.'

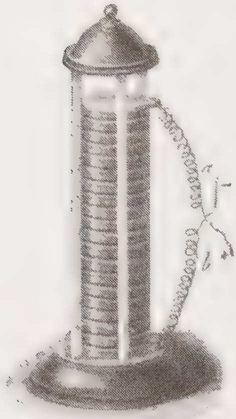


Fig. 519.

On Volta's view the union of one zinc and one copper forms *a couple*; in the annexed figure twenty couples are superposed, separated from each other by pieces of cloth, and all arranged in the same order, so that the zinc at the top is positive and the copper at the bottom negative. Since its invention it has been greatly modified; but the general name of pile is still frequently used for apparatus of the same kind, and the electricity thus furnished is spoken of as *voltaic* or *galvanic electricity* in honour of the discoverers.

491. **Production of electricity by chemical action.**—The contact theory which Volta had propounded, and in which he explained the action of the pile, soon encountered objectors. Fabroni, a countryman of Volta, having observed that in the pile the discs of zinc became oxidised in contact with the acidulated water, thought that this oxidation was the principal cause of the disengagement of electricity. In England, Wollaston soon advanced the same opinion, and Davy supported it by many ingenious experiments.

It is true that in the fundamental experiment of the contact theory (489) Volta obtained signs of electricity. But De la Rive showed that if the zinc be held in a wooden clamp all signs of electricity disappear, and that the same is the case if the zinc be placed in gases, such as hydrogen or nitrogen, which exert upon it no chemical action. De la Rive accordingly concluded that in

Volta's original experiment the disengagement of electricity is due to the chemical actions which result from the perspiration and from the oxygen of the atmosphere. It must be admitted that the question as to the origin of electricity in the voltaic pile is still an open one.

By a variety of analogous experiments it may be shown that all cases of chemical action are accompanied by a disturbance of the electric equilibrium. This is the case whether the substances concerned in the action are in the solid, liquid, or gaseous state, though of all chemical actions those between metals and liquids are the most productive of electricity. All the resultant effects may be explained on the general principle that when a liquid acts chemically on a metal the liquid assumes the *positive* electric, and the metal the *negative* electric, condition.

Hence we arrive at a theory of the origin of electricity in the voltaic pile which will be best illustrated by reference to the following simple experiment.

492. **Current electricity.**—When a plate of zinc and a plate of copper, each with a wire attached, are partially immersed in dilute sulphuric acid without touching each other, it may be shown by a delicate condensing electroscope that the wire attached to the zinc plate possesses a feeble charge of negative, and that attached to the copper plate a feeble charge of positive, electricity. There will be no apparent chemical action if the zinc is pure, or is commercial zinc amalgamated with mercury. If now the plates are placed in contact, either directly or by means of the attached wires, chemical action begins and hydrogen is given off in large quantities from the surface of the copper (fig. 520); and if the connecting wire be examined it will be found to possess the remarkable properties characteristic of the discharge of opposite electricities—the heating, the magnetic, the magnetising, the luminous effects. So long as the metals remain in the liquid, the opposite electric conditions of the two plates discharge themselves by means of the wire, but are instantaneously restored, and as rapidly discharged; and, as these successive charges and discharges take place at such infinitely small intervals of time that they may be considered continuous, the wire is said to be traversed

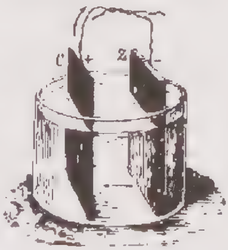


Fig. 520.

by an electric or voltaic *current*. The direction of this current *in the connecting wire* is assumed to be from the copper to the zinc, and in the liquid from zinc to copper; or, in other words, this is the direction in which the positive electricity flows, the direction of the negative current in the wire being from the zinc to the copper.

493. **Identity of frictional and voltaic electricity.**—In speaking of frictional and voltaic electricity, we must not be considered as implying that there is any essential distinction between them. There is only a difference in the mode in which the electricity manifests itself. In the former we have effects due to stationary charges, so that it is often called *static* electricity; in the latter we deal with the effects of a continuous flow, and thus we call it *dynamic* electricity. Frictional and voltaic electricity differ in degree and not in kind; an electric current may be regarded as a succession of electric discharges, and conversely an electric discharge may be regarded as a current of extremely short duration. All the effects which can be produced by frictional electricity can also be produced by dynamic electricity, and conversely all the effects which we shall afterwards describe as producible by voltaic electricity can likewise be produced by frictional electricity. The practical distinction between them is that just those effects which are most easily produced in the one way are most difficult to produce in the other. Thus, for instance, the simplest of all experiments in frictional electricity is that by which we demonstrate the existence of a state of electrification, the attraction of light bodies when a stick of sealing-wax is rubbed. The attraction of bodies can indeed be shown by voltaic electricity, but it requires the association of a great number of cells to produce even a very slight deflection in a delicately suspended pith ball. On the other hand, the deflection of a magnetic needle is, as we shall see, the simplest way of showing the existence of a voltaic current, and can be effected by the crudest apparatus. A magnetic needle can indeed be deflected by means of an electric machine, but it requires special precautions, and a delicate galvanometer (521). The production of the electric spark is one of the simplest experiments; with a small electric machine a spark of two centimetres in length is easily produced. To produce a spark a millimetre long by means of a voltaic battery it would be necessary to employ not less than 4,000 cells.

494. **Voltaic couple. Electromotive series.**—The arrange-

ment lately described, consisting of two metals and a conducting liquid in which they are placed, constitutes a *simple voltaic element, couple*, or *cell.* So long as the metals are not in contact, the circuit is said to be *open* ; when they are connected, either by being placed in direct contact or by the intervention of a conductor, it is said to be *closed.*

For the production of a voltaic current it is not necessary that one of the metals be unaffected by the liquid, although it is best so, but merely that the chemical action upon the one be greater than upon the other. The metal which is most attacked is called the *positive* or active plate, and that which is least attacked the *negative* or inactive plate. The positive metal determines the direction of the current which proceeds *in* the liquid from the positive to the negative plate, and *out* of the liquid through the connecting wire from the negative to the positive plate.

In speaking of the direction of the current, the positive current is always understood ; to avoid confusion, the existence of the current in the opposite direction, the negative current, is tacitly ignored.

As a voltaic current is produced whenever two metals, placed in a liquid which acts more powerfully upon one than upon the other, are connected by a conductor, there is great choice in the mode of producing such currents. In reference to their electric deportment, the metals have been arranged in what is called an *electromotive series*, in which the most *electropositive* are at one end, and the most *electronegative* at the other. Hence, when any two of these are placed in contact in dilute acid, the current in the connecting wire proceeds from the one lower in the list to the one higher. The principal metals are as follows :—

1. Zinc.	4. Nickel.	7. Gold.
2. Lead.	5. Copper.	8. Platinum.
3. Iron.	6. Silver.	and 9. Graphite (non-metal).

Thus iron placed in dilute sulphuric acid is electronegative towards zinc, but is electropositive towards copper ; copper, in turn, is electronegative towards iron and zinc, but is electropositive towards silver, platinum, or graphite.

The force due to the difference in the chemical action of a liquid upon two metals placed in it is called the *electromotive force* of the cell so formed. The terminal connected with the less active plate

is at a higher potential than that connected to the more active plate, and the *electromotive force* of the cell is equal to the difference of potential between the terminals, and is greater in proportion to the distance of the two metals from one another in the series. That is to say, it is greater the greater the difference between the chemical action upon the two metals immersed. Thus, the electromotive force of a cell formed of zinc and platinum is greater than if zinc and iron, or zinc and copper, were employed.

The electromotive force of a cell depends on the nature of the metals and of the liquid, and not at all on their dimensions; that is, the electromotive force of a zine-copper-sulphuric-acid cell is the same whether the metals be in the form of thin wires or large plates; just as the pressure of water at any point is proportional to the depth of this point below the surface and not to the mass (90). Indeed, we may pursue this parallel further, and show many such analogies between electric and hydrostatic phenomena; just as a difference of level in the liquid in two communicating vessels determines the flow, so in like manner it is a difference in electric level which gives rise to those phenomena which we call motion of electricity.

495. **Poles and electrodes.**—If the wire connecting the two terminal plates of a voltaic couple is cut, it is clear, from what has been said about the origin and direction of the current, that positive electricity will be found at the end of the wire attached to the copper plate, and negative electricity on the wire attached to the zinc plate. These terminals are called the *poles* of the battery. For experimental purposes, more especially in the decomposition of salts, plates of platinum are attached to the ends of the wires. Instead of the term 'pole,' the word *electrode* (ἤλεκτρον and ὁδός, a way) is now commonly used, for these are the *ways* through which the respective electricities emerge. It is important not to confound the positive *plate* with the positive *pole*. The copper terminal of a zinc-copper-acid cell is the positive pole, the zinc terminal the negative pole; and *the current* flows *in the connecting wire* from copper to zinc and *in the acid* from zinc to copper.

496. **Voltaic battery.**—When a series of voltaic cells are arranged in such a manner that the zinc of one cell is connected with the copper of another, the zinc of this with the copper of another, and so on, such an arrangement is called a *voltaic battery*; and by its means the effects produced by a single cell are capable of being very greatly increased.

The earliest of these arrangements was the voltaic pile devised by Volta himself (490).

It will be readily seen that this is merely a series of simple voltaic couples, the disc of moistened cloth acting as the liquid, and that the terminal zinc is the negative and the terminal copper the positive pole. The double plates at top and bottom are unnecessary, and the removal of the terminal zinc and copper plates does not affect the electromotive force of the pile, which depends only upon the number of discs of moistened cloth. From the mode of its arrangement, and from its discoverer, the apparatus is known as the *voltaic pile* (490), a term applied to all apparatus of this kind for accumulating the effects of dynamic electricity.

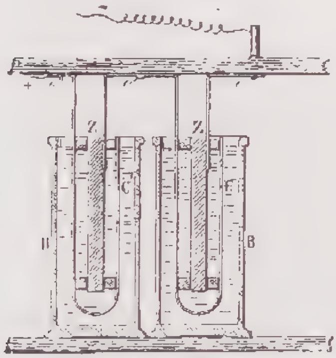


Fig. 521.

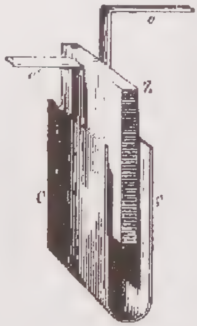


Fig. 522.

The distribution of electricity in the pile varies according as it is in connection with the ground by one of its extremities, or as it is insulated by being placed on a non-conducting cake of resin or glass.

In the former case, the end in contact with the ground is at zero potential, and the rest of the apparatus only contains one kind of electricity, the potential increasing (numerically) from the earthed pole to the free pole ; this is negative if a copper disc is in contact with the ground, and positive if it is a zinc disc.

If the pile is insulated the electricity is not uniformly distributed. By means of the proof-plane and the condensing electroscope (468) it may be demonstrated that the middle part is in a neutral state or at zero potential, and that one half is charged with positive

and the other with negative electricity, the potential increasing numerically from the middle to the ends. The half terminated by a zinc is charged with negative electricity, and that by a copper with positive electricity. The difference of potential between the poles, that is, the electromotive force of the battery, is the same whether the battery is insulated or not. The effects of the pile will be discussed in other places.

The original form of the voltaic pile possesses now only an historic interest, for it has a great many inconveniences; among these is the fact that the weight of the discs of zinc and copper is

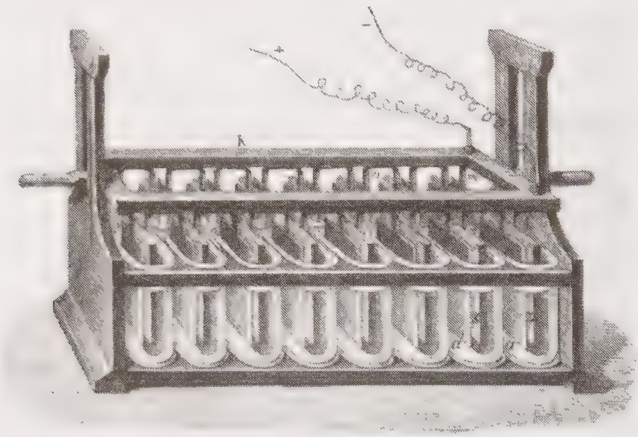


Fig. 523.

so great that it presses out the acidulated liquid from the discs, and the electric action is soon weakened. The pile has received a great many improvements, the principal object of which has been to facilitate manipulation, to produce greater electromotive force (494), and to lessen the resistance.

One of the earliest of these modifications was the crown of cups, or *couronne des tasses*, invented by Volta himself; an improved form of this is known as *Wollaston's battery* (fig. 521).

Fig. 521 gives a vertical section of two consecutive Wollaston's cells. The metals are zinc and copper, and the liquid acidulated water. Fig. 522 represents the arrangement of one of these couples; it consists of a thick sheet of zinc, Z, and a strip of copper,

o, by which the zinc can be connected with the next cell. A plate of copper, CC, is bent so as to surround the plate of zinc without touching it, contact being prevented by small pieces of cork. The plate, C, is provided with a copper tongue, *o′*, which is soldered to the zinc of the next cell, and so forth.

Fig. 523 represents a battery of sixteen such cells united in two parallel series of eight each. All the metals are fixed to a cross frame of wood, by which they can be raised or lowered at pleasure. When the battery is not wanted, the metals are lifted out of the liquid. The water in these vessels is usually acidulated with $\frac{1}{16}$ sulphuric and $\frac{1}{20}$ nitric acid.

497. **Enfeeblement of the current produced by batteries.**—The batteries already described, which consist essentially of two metals and one liquid, labour under the objection that the currents produced rapidly diminish in intensity.

This is principally due to three causes. The first is the decrease in the chemical action owing to the neutralisation of the sulphuric acid by its combination with the zinc. This is a necessary action, for upon it depends the current; it therefore occurs in all batteries, and is without remedy, except by replacement of acid and zinc. The second is due to what is called *local action*. Suppose, for example, that we have a plate of perfectly pure zinc placed in dilute acid (fig. 524), the plate being varnished so that it is not acted on by the acid; and suppose now in the point *a* a piece of the protecting varnish scratched away, while a small steel point is driven in at *b*. We have here all the conditions for the production of an electric current: two different metals in metallic connection in a liquid which acts upon them unequally; the effect is that a current is produced from *a* to *b* through the liquid, and from *b* to *a* through the zinc itself, and the zinc at *a* is eaten away.

Fig. 524.

In effect all ordinary zinc contains metallic impurities, such as lead and iron, which realise the above conditions, forming innumerable local currents, and which rapidly wear away the active plate without contributing anything to the general current. They are remedied by *amalgamating* the zinc with mercury. The process of amalgamation is as follows. The zinc plate is rubbed over with a piece of flannel soaked in dilute acid, and a few drops of mercury poured over the cleaned metal. The mercury rapidly spreads and

combines with the zinc, forming a bright amalgam. Amalgamated zinc behaves in the cell exactly like pure zinc: that is, no local currents are formed, there is no *local action.* The third and most important cause of the enfeeblement of the action of the cell is what is called *the polarisation of the inactive plate.* In the fundamental experiment (fig. 520), when the circuit is closed zinc sulphate is formed, which dissolves in the liquid, and at the same time a layer of hydrogen gas is deposited on the surface of the copper plate, which is then said to be *polarised.* Now, it has been found that the hydrogen deposited in this manner on metallic surfaces acts far more energetically than ordinary hydrogen.

This active hydrogen is more electropositive than zinc, and therefore acts towards zinc as zinc itself acts towards copper. Thus, as soon as hydrogen begins to be deposited on the copper plate there is set up an electromotive force opposed to the main electromotive force of the cell, the *effective* electromotive force being the difference of the two. Hence the current which flows in the circuit must diminish, for the current is proportional to the electromotive force, just as the flow of water in a pipe is proportional to the *hydrostatic* pressure.

498. **Constant cells.**—The serious objections to the use of what are called *single fluid* cells have led to their abandonment, and they are now generally replaced by *two fluid* cells, or those with two liquids, which are also called *constant* cells, because their electromotive force is without material alteration for a considerable period of time. The essential point to be attended to in securing constant electromotive force is to prevent the polarisation of the inactive metal; in other words, to hinder any permanent deposition of hydrogen on its surface. This is effected by placing the inactive metal in a liquid upon which the hydrogen can act chemically.

No cell is known whose electromotive force (generally written E.M.F.) is strictly constant under all conditions. A cell or battery is commonly spoken of as constant when, after it has been in action for several hours, its E.M.F. has undergone only a small percentage diminution.

499. **Daniell's cell.**—This was the first form of the constant cell, and was invented by Daniell in the year 1836. As regards the constancy of its action, it is still the best of all constant batteries. Fig. 525 represents the ordinary French form of a single cell. A glass or porcelain vessel, V, contains a saturated solution of copper sulphate, in which is immersed a copper

cylinder, C, open at both ends and perforated by holes. At the upper part of this cylinder there is an annular shelf, G, also perforated by small holes, and below the level of the solution: this is intended to support crystals of copper sulphate to replace that decomposed as the electric action proceeds. Inside the cylinder is a thin porous vessel, P, of unglazed earthenware. This contains either a solution of common salt or dilute sulphuric acid, in which is placed the cylinder of amalgamated zinc, Z. Two thin strips of copper, *p* and *n*, fixed by binding screws to the copper and to the zinc, serve for connecting the cells in series.

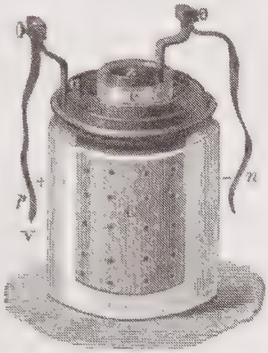


Fig. 525.

When the circuit of a Daniell's cell is closed, the hydrogen which results from the action of the dilute acid on the zinc, before it can reach the copper plate, meets the copper sulphate, which it reduces, with the formation of sulphuric acid and metallic copper, the copper being deposited on the surface of the copper plate. In this way the copper sulphate in the solution is taken up, and, if it were all consumed, hydrogen would be deposited on the copper, and the current would lose its constancy. This is prevented by the crystals of copper sulphate, which keep the solution saturated. The sulphuric acid produced by the decomposition of the sulphate permeates the porous cylinder, and tends to replace the acid used up by its action on the zinc; and as the quantity of sulphuric acid formed in the solution of sulphate of copper is regular and proportional to the acid used in dissolving the zinc, the action of this acid on the zinc is regular also, and thus a constant current is maintained.

The construction of the Daniell cell may be simplified, and the outer vessel of glass or porcelain dispensed with, by making the copper plate serve as the containing vessel. When used in this way it has a narrow perforated ledge near the top for copper sulphate crystals, and the porous pot just fits inside this. The copper vessel must be carefully made, and the solder used for brazing protected from the action of the liquid in the cell, otherwise local currents are set up, the more oxidisable metal is eaten away, and the vessel begins to leak.

500. **Minotto's cell. Gravity battery.**—We may mention here two cells which are modifications of that of Daniell, and which are remarkable for their economy and the facility with which they are constructed. The object is to get rid of the porous pot, the use of which is attended with numerous drawbacks.

The Minotto cell (fig. 526) consists of a glass or earthenware vessel, at the bottom of which is a copper disc, to which is riveted an insulated copper wire. This is surrounded by a thick layer of crystals of sulphate of copper, and on the latter a flannel disc is placed. Next comes a thick layer of sawdust, and on this rests a round zinc block, to which a wire is attached. The sawdust is

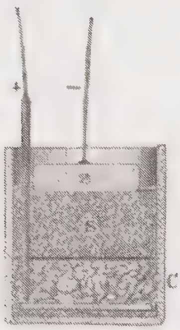


Fig. 526.

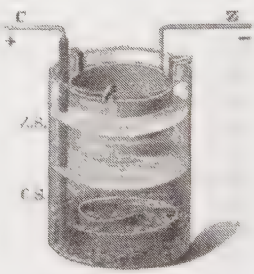


Fig. 527.

soaked in water to which a few drops of acid have been added and the excess of water squeezed out. There is thus a solution of copper sulphate at the bottom, and one of acidulated water at the top. When the circuit is closed by connecting the poles of the cell, an action is set up which is identical with that of the ordinary Daniell. For arrangement in battery the zinc block is cast on to the wire from the copper plate. This battery is largely used for testing the fuses used in firing guns, exploding mines, etc., as its E.M.F. is constant and its resistance may be made very large by squeezing the moisture out of the sawdust.

Another form is known as the *gravity battery*, in which the porous diaphragm is altogether dispensed with. The form depicted in fig. 527 is that of Calland. The copper plate, in this case a spiral copper band, provided with an insulated wire, C, is immersed in a saturated solution of copper sulphate, while on the

top of this a solution of zinc sulphate floats in consequence of its lower specific gravity. The zinc block rests, by means of lugs, on the top of the vessel. When the terminal wires are connected, action is at once set up.

Such elements as these cannot be moved about, for otherwise the liquids would mix, metallic copper would be deposited on the zinc plate and give rise to local action. But they are well adapted for working heavy telegraph lines in permanent stations, and are largely used in France and in Austria.

501. **Bunsen's cell.**—*Bunsen's cell* was invented in 1843 : it is in effect a Daniell's cell, in which nitric acid is substituted for solution of copper sulphate, and in which copper is replaced by a cylinder

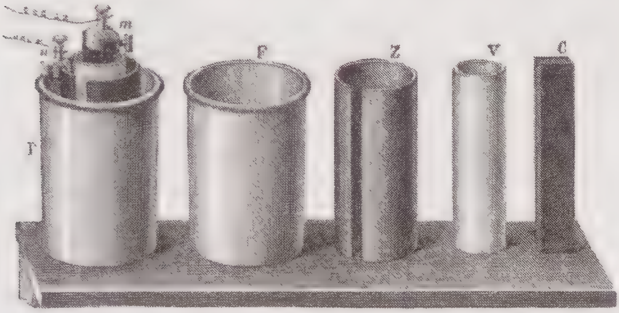


Fig. 528.

of carbon. This is made either of the *graphitoidal carbon* deposited in gas retorts, known as *gas graphite*, or by calcining in an iron mould an intimate mixture of coke and bituminous coal, finely powdered and strongly compressed. Both these modifications of carbon are good conductors. Each cell consists of the following parts : 1, a vessel, F (fig. 528), either of stoneware or of glass, containing, as in Daniell's, dilute sulphuric acid ; 2, a hollow cylinder, Z, of amalgamated zinc ; 3, a porous vessel, V, in which is strong nitric acid ; 4, a cylinder of carbon, C, prepared in the above manner. In the vessel F the zinc is first placed, and in it the porous pot containing the carbon, as seen in P. To the carbon is fixed a binding screw, *m* (fig. 529), to which a copper wire is attached, forming the positive pole. The zinc is provided with a similar binding screw, *n*.

In Bunsen's cell the hydrogen resulting from the action of the dilute sulphuric acid on the zinc makes its way towards the surface

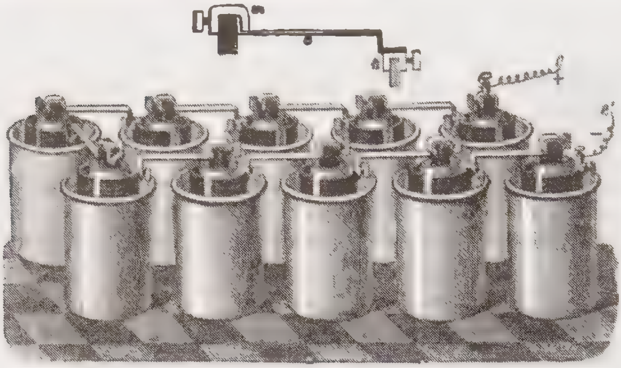


Fig. 529.

of the carbon. This being surrounded by nitric acid, the hydrogen decomposes this acid, forming water and *hyponitrous acid*

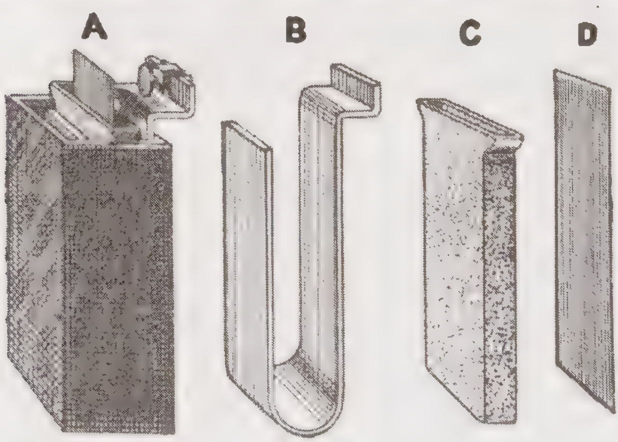


Fig. 530.

(nitrogen tetroxide), which dissolves, or is disengaged as reddish-brown fumes. And, though the hydrogen is most completely

oxidised by the nitric acid, the action of these nitrous fumes is very noxious. They may, however, be almost completely got rid of by adding to the vessel containing the nitric acid a small quantity of powdered potassium bichromate.

The cells are arranged to form a battery (fig. 529) by connecting each carbon to the zinc of the following one by means of the clamps, *mn*, and a strip of copper, *c*, represented in the top of the figure. The copper is pressed at one end between the carbon and the clamp, and at the other it is soldered to the clamp *n*, which is fitted on the zinc of the following element, and so forth. The clamp of the first carbon and that of the last zinc are alone provided with binding screws, to which are attached the wires.

502. **Grove's cell.**—This differs from Bunsen's in form and in the substitution of platinum for carbon; otherwise the two cells are identical, and the chemical action is the same in both. Fig. 530, A, shows the arrangement. A rectangular sheet of platinum foil, D, is supported in a narrow porous pot, C, containing strong nitric acid. The zinc plate, B, is bent in the form of a U, and the flat porous pot placed between its two branches. The outer vessel, which contains the dilute sulphuric acid, is made of glass or glazed earthenware or *vulcanite*, a combination of india-rubber and sulphur, also called *hard rubber*.

The Grove cell and the Bunsen cell have practically the same E.M.F. The Grove is the more expensive on account of the platinum in it; but it is more compact and convenient to manipulate than the Bunsen.

503. **Leclanché's battery.**—Each cell (fig. 531) consists of a slab of carbon, L, placed in a porous pot, which is then tightly packed round with a mixture of pyrolusite (peroxide of manganese) and coke, M. The porous pot is contained in an outer vessel, G, in which is a rod of the electropositive metal zinc, Z. The exciting liquid is a solution of sal-ammoniac.

The essential part of the action is as follows :—The hydrogen which results from the action of the zinc and sal-ammoniac coming in contact with the manganese peroxide combines with some of its oxygen with the formation of water, and so the carbon plate is saved from polarisation, for the hydrogen ceases to exist as such. When the action is very rapid, or, in other words, when the strength of the current exceeds a certain limit, the hydrogen is produced faster than it can be disposed of, and accumulates round the carbon

plate, and, in consequence, the E.M.F. of the cell rapidly falls. But if the cell is left on open circuit, the hydrogen is gradually oxidised and the cell recovers its original E.M.F. Leclanché cells are extremely useful for electric bells, firing mines, and other purposes where a tolerably strong current is wanted intermittently. They are not constant in the sense in which the Daniell and the Grove cells are constant, for their E.M.F. runs down when they are kept on short circuit, but they have the merits of portability,

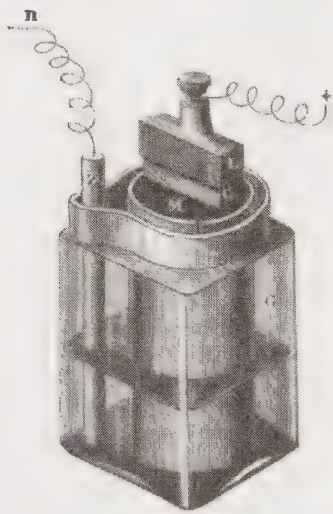


Fig. 531.

Fig. 532.

cleanliness, and cheapness. The E.M.F. is intermediate between those of Grove and Daniell.

504. The **Bichromate cell** may be mentioned as one which may be used when a high electromotive force is required for a comparatively short time. Carbon and zinc are the solid elements used in it, and the liquid is a mixture of strong sulphuric acid and saturated solution of potassium bichromate. It is, like the Leclanché, a one-fluid cell. The hydrogen, due to the solution of the zinc in the acid, is oxidised by the bichromate, and as it is thus prevented from polarising the carbon plates the cell preserves its E.M.F. for

some time. The amalgamated zinc plate is embraced on its two sides by slabs of gas carbon which are in metallic connection with each other, but insulated from the zinc. The zinc plate is attached to a rod which slides in a tube (fig. 533) and enables the plate to be immersed in the liquid and to be withdrawn when the cell is not in use. The E.M.F. of this cell is about 10 per cent. higher than that of the Grove or Bunsen.

Fig. 533.

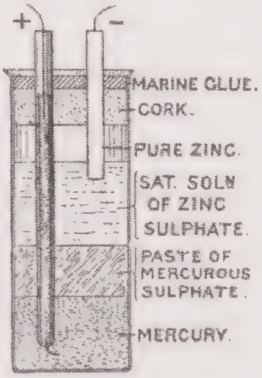


Fig. 534.

505. **Latimer Clark cell.**—This cell is intended as a standard of E.M.F., and not as a means of producing an electric current. Fig. 534 illustrates the usual form. The glass cell, about 4 inches high and 1½ inch in diameter, contains mercury at the bottom, and on this a paste of mercurous sulphate (Hg_2SO_4). The electro-positive element is pure zinc, which dips into a saturated solution of zinc sulphate. The E.M.F. of this cell is 1·434 volt (507) at 15° C. All cells made up with the above materials, carefully prepared, are found to have the same E.M.F., which remains constant so long as the cell is not short-circuited.

506. **Zamboni's dry battery.**—A dry battery is one each cell of which consists of two solid substances separated by a sheet of paper, which, though apparently dry, contains ordinarily a certain amount of moisture. A Zamboni's dry battery is constructed as follows: a sheet of paper is smeared over with a thin layer of finely powdered manganese peroxide, and discs about an inch in diameter punched out of it. Similar discs are punched from a

sheet of tinfoil. The discs, alternately tinfoil and paper, are built up into a pile of about a thousand, tightly pressed together and terminated by suitable metal pieces which serve as poles. Such a battery has a high electromotive force, the electrification on its poles being sufficient to attract and then repel a pith ball (430), but on account of its high resistance the current derived from it is very minute. The pole connected with the manganese peroxide is the positive, the tinfoil terminal being the negative pole.

507. **Electromotive force, current, resistance.**—When the poles of a battery are conducted by a conductor of any kind and an electric current flows through it, electricity goes round and round the circuit. The cause of the flow of electricity is the electromotive force of the battery, and for a given E.M.F. the quantity of electricity which passes any section of the circuit in one second (which is called the *strength of the current*) depends upon the opposition which the current meets with, either in the battery itself or in the conductors by which its poles are connected. We have thus three things to think about in contemplating an electric circuit: (1) the E.M.F., which is the cause of the flow of electricity; (2) the strength of the current; and (3) the resistance of the circuit, which is conveniently divided into internal resistance (that of the battery) and external resistance. The strength of the current is greater the greater the E.M.F. and the less the opposing resistance.

The unit of electromotive force is a *volt*. The E.M.F. of the cells given below are expressed in terms of a volt.

Cell.	*E.M.F.*	*Cell.*	*E.M.F.*
Zinc-acid-copper	·5 to ·8	Latimer Clark	1·434
Daniell Minotto Gravity Daniell	1·1	Grove Bunsen	1·85
		Bichromate	2·00
Leclanché	1·45–1·50		

The unit of resistance is called an *ohm*. An ohm is defined as the resistance of a column of mercury 106·3 centimetres long and 1 sq. millimetre in cross section, but it may be realised in any material. For instance, 76 yards of copper wire, No. 18 S.W.G., has a resistance of one ohm. As copper conducts electricity about 14 times as well as German silver, only about 5½ yards of wire of

the same gauge of the latter material would be required to offer a resistance of one ohm. The resistance of a wire varies directly as its length and inversely as its cross section ; it also depends upon the material of the wire. The *specific resistance* of a material is the resistance in ohms of a centimetre cube of the material between opposite faces. The *specific conductivity* of a material is the reciprocal of its specific resistance. The resistance of a voltaic cell is less the larger the area of the plates and the closer they are together. It depends also upon the conductivity of the liquid or liquids by which the plates are separated. The E.M.F. of a cell is independent of its size ; thus the E.M.F. of a Daniell cell is 1·1 volt, whether the cell be as small as a thimble or as large as a barrel. But its internal resistance is a function of its size. The E.M.F. of a cell is the only definite thing about it, and whether the current it produces when its poles are joined is large or small depends solely upon the internal and external resistances in the circuit.

The unit quantity of electricity is called a *coulomb*. When the conditions are such that one coulomb passes any cross section of the circuit in each second, the strength of the current is said to be *one ampere*. This is the unit of current.

CHAPTER VIII

EFFECTS OF THE VOLTAIC CURRENT

508. **Physiological effects.**—The remarkable phenomena due to electric currents may be classed under the heads physiological, chemical, mechanical, and physical effects; and these latter may be again subdivided into the thermal, luminous, and magnetic effects.

When the terminals of a battery are grasped by the two hands, the current, unless the battery consists of a very large number of cells, is feeble, on account of the large resistance of the human body. The chief part of this resistance is in the skin, and if the hands are moistened with acidulated or saline water, the skin resistance is much diminished and a stronger current passes through the body. In these circumstances a decided *shock* is experienced at the moment of grasping the terminals, and a tingling sensation is felt in the arms and hands so long as the current flows. But the *chief physiological* effect is noticed at the moment when the terminals are laid hold of, or let go; that is, when the current strength is changing.

A small E.M.F. when applied to the parts over the eye produces a luminous effect; in the neighbourhood of the ears a rushing sound; and when the two poles are placed on the tongue the positive has an acid and the negative an alkaline taste. This, indeed, is a convenient test for the conditions of a current Sensitive plants are also affected when the terminals of a battery consisting of a large number of cells are applied to them.

509. **Heating effects.**—When a voltaic current is passed through a metal wire, the wire becomes heated and even incandescent if it is very short and thin. With a powerful battery all metals are melted, even iridium and platinum, the least fusible of metals. Carbon is the only body which hitherto has not been fused by it.

Fine wires of lead, tin, zinc, copper, gold, silver, iron, and platinum may be melted by sufficiently strong currents, and even volatilised, with differently coloured sparks. Iron and platinum burn with a brilliant white light ; lead with a purple light ; the light of tin and of gold is bluish white ; the light of zinc is a mixture of white and gold ; copper and silver give a green light.

The law which expresses the relation between the heating effect in a voltaic circuit, and the strength of the current and resistance of its various parts, has been investigated by Joule and is generally known by his name.

Joule showed that the amount of heat produced in a circuit varies as the square of the strength of the current, as the resistance of the circuit, and, of course, as the time. In the case of any little bit of the circuit the heat per unit of time varies as the resistance of that bit and as the square of the current strength. Joule's law may be demonstrated by means of an apparatus called the galvano-thermometer (fig. 535). A wide-mouthed stoppered bottle is fixed upside down, with its stopper, *b*, in a wooden block ; the stopper is perforated so as to give passage to two thick platinum wires, connected at one end with binding screws, *s s*, while their free ends are provided with platinum cones to which different wires under investigation can be affixed ; the vessel contains alcohol, the temperature of which is indicated by a thermometer, *f*. The current is passed through the platinum wires, and its strength measured by means of a tangent galvanometer (522) interposed in the circuit. By observing the increase of temperature in a given time, and knowing the weight of the alcohol, the mass of the wire, the specific heat, and the calorimetric values of the vessel and of the thermometer, the total amount of heat which is produced by the current in a given time can be calculated.

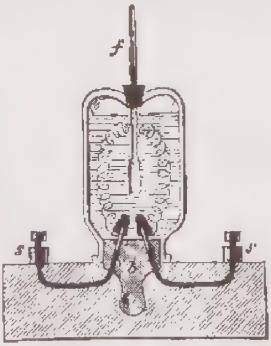


Fig. 535.

By altering the current that passes through the wire, which may be done by increasing or diminishing the number of cells in the battery, we may prove, by repeating the calorimetric experiment

with each change of current, that the heat produced varies as the square of the strength of the current. Again, by including in the circuit two or more apparatus like that of fig. 535, containing wires of different but known resistances, it may be proved that the heat is directly proportional to the resistance. Thus Joule's law is established.

When a circuit containing a voltaic battery is closed, a certain amount of heat is produced, which is distributed over the whole circuit—the liquid, the plates, and the connecting wire. The quantity of this heat depends on the consumption of the attacked metal, which is practically always zinc. The solution of a definite weight of zinc produces a definite quantity of electricity to flow round the circuit, and this produces a definite amount of heat ; if this solution takes place rapidly, the temperature is higher than if it takes place slowly ; but the total quantity in each case is the same ; just as the total quantity of heat produced by burning a given weight of coal is the same whether it is burnt fast or slowly.

Again, the distribution of heat in the circuit follows the simple law that the heat produced in any particular part of the circuit bears the same ratio to the total heat that the resistance (507) of that particular part bears to the total resistance. Thus, if the resistance of the connecting wire outside the cell is twice as great as the internal resistance of the cell, the heat in the connecting wire will be twice that in the liquid, or two-thirds of the total heat.

Fig. 536.

If the current passes through a chain of platinum and silver wires of equal sizes (fig. 536), the platinum, *p*, becomes more heated than the silver, *s*, from its greater resistance ; and with a suitable current the platinum may become incandescent while the silver remains dark. This experiment was devised by Children.

Several interesting illustrations of the heating effect of the current may be made by means of *Foster's apparatus*, represented in fig. 537, which consists of two glass bulbs provided with stop-

cocks and attached to U-tubes containing a coloured liquid; they are, in fact, two air-thermometers. Stout copper wires lead from the binding screws and are fitted air-tight by means of corks in the bulbs; to these ends platinum and other wires of various lengths and thicknesses may be fixed.

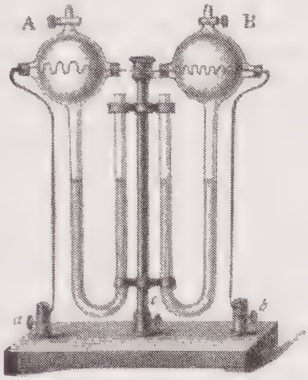


Fig. 537.

If the poles of a couple of Grove's cells are connected with *a* and *c*, or with *c* and *b*, the depression of the liquid at once shows that a heating effect is produced. If the spiral wire in A has only half the resistance of that in B, then, when the cells are connected up with *a* and *b* so that the current traverses both wires, the depression of the liquid in A will only be one-half that in B, showing that the heating effect in any part of a circuit is proportional to the resistance of that part.

510. **Applications of the heating effect.**—The heating effects of the voltaic current are used in firing mines for military purposes and for blasting operations. A simple form of fuse for this purpose is shown in fig. 538, which represents a round piece of wood, about half an inch in diameter, in which two grooves are cut. Two copper wires, *a a* and *b b*, insulated except at the free ends, fit in these grooves and pass through holes bored in the wood without touching each other, and are kept in their place by being wrapped round with fine thread. The ends bared are connected by a thin platinum wire *ab*, and the other ends of the wire are joined to stout copper wires which lead to the battery. Round the fuse is wrapped a paper case (not represented in the figure) which is filled with fine powder, and, being closed, the fuse is then placed in a bag of powder in the place where the explosion is to take place. Now, we have seen that in any part of a voltaic circuit the heating effect is the greater according as the *resistance* of that part of the circuit is greater. This is the reason for having a thin platinum wire, for the resistance

Fig. 538.

is greater the thinner the wire, and, moreover, platinum is a metal of comparatively high specific resistance (507). Accordingly, when an E.M.F. of from 5 to 10 volts is applied to the circuit, the thin platinum wire instantaneously becomes incandescent, and explodes the powder.

A useful application of the heating effect of the current is made in the surgical operation of *cauterisation*. If a carbuncle or other enlargement is to be removed, a thin platinum wire which forms part of a voltaic circuit is moved across it; this cuts like a knife, and at the same time cauterises the surface thus cut. It has been observed that when the temperature of the wire is about 600° C. the combustion of the tissues is so complete that there is no hæmorrhage; while at 1,500° the action of the wire is like that of a sharp knife.

Another application of the heating effect is to what are called *safety catches*, or *cut-outs*. These are lengths of wire or strip, of an alloy of lead and tin, interposed in the circuit of the powerful currents used for electric lighting and the like. Their dimensions are so calculated that when the current attains a certain strength, the heat generated is sufficient to melt them, and thus break the circuit. The form represented in fig. 539 is a lead-tin wire on which is cast a lead shot; when the temperature is high enough to soften the wire, the weight of the shot is sufficient to promptly break it and thus stop the current at once.

Fig. 539.

511. **Luminous effects.**—On breaking a voltaic circuit a spark is obtained at the point of rupture, which is frequently of great brilliance. These luminous effects are obtained, when the battery is sufficiently powerful, by bringing the two electrodes very nearly in contact; a succession of bright sparks springs across the interval, which follow each other with such rapidity as to produce a continuous light. With eight or ten of Grove's cells brilliant luminous sparks are obtained by connecting one terminal of the battery with a file, and moving its point along the teeth of another file connected with the other terminal.

The most beautiful effect of the electric light is obtained when

two pencils of charcoal are connected with the terminals of a powerful battery or dynamo in the manner represented in fig. 540. The charcoal *b* is fixed, while the charcoal *a* can be raised and lowered by means of a rack and pinion motion, *c*. The two charcoals being placed in contact, the current passes, and their ends soon become incandescent. If they are then removed to a distance of about the tenth of an inch, the air between them is heated, little particles become detached, are heated to incandescence, and travel from one carbon to the other; they thus form a luminous arc ex-

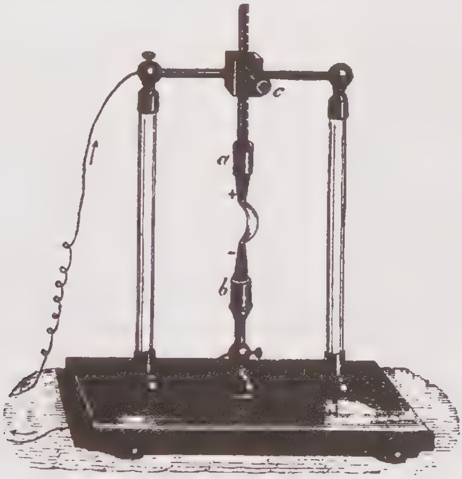


Fig. 540.

tending between the two points, which has an exceedingly brilliant lustre, and is called the *voltaic* or *electric arc.*

The length of this arc varies with the strength of the current. In air, with a battery of 600 cells, it may exceed two inches. If the charcoal attached to the positive pole is examined, it will be found to have become worn away, forming a crater-like hollow, while the negative charcoal is worn to the form of a blunt point, and to a much less extent than the positive (fig. 541). It seems that the carbon is mechanically transported from the positive to the negative terminal, and that this is the manner in which the transmission of the electricity between the two poles is effected.

The small globules seen in the figure are mineral impurities in the carbon, which are melted at the high temperature of the voltaic arc.

For public illumination the carbons are connected with a mechanism, actuated by the current itself, which keeps the carbon poles at a suitable distance apart, a condition necessary for the permanence and steadiness of the light.

There are numerous and varied forms of such apparatus, and usually they are complicated and expensive ; but a general idea of the way in which they act may be obtained by reference to a simple form represented in fig. 542. The current enters the lamp by a wire attached to a binding screw on the base of the instrument, passing up the pillar by the small electromagnet (537) to the centre pillar, along the top of the horizontal bar, down the left-hand bar, through the two carbons, and away by a wire attached to a binding screw on the left hand. A tube holding the upper carbon slides freely up and down another tube at the end of the cross-piece, and would by its own weight rest on the lower carbon, but the electro-magnet is provided with a keeper, to which is attached a rest that encircles the carbon tube and grasps it. When the electro-magnet works and attracts the keeper, the rest tightens and thereby prevents the descent of the carbon. When the keeper is not attracted, the rest loosens, and the carbon holder descends.

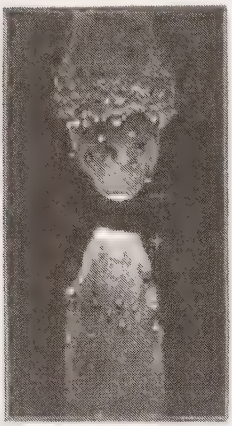


Fig. 541.

When the two carbons are at rest and the circuit is completed, the current traverses both carbons, and no light is produced. But if the upper carbon be raised ever so little a brilliant light is emitted. When the lamp is thus once set to work, the rod attached to the upper carbon may be let go, and the magnet will afterwards keep the lamp at work. For when some of the carbon is consumed, and the current in consequence is weakened, the magnet loses some of its power, and the keeper loosens its hold on the upper carbon, which descends by its own weight. As the carbons approach each other the current strength rises ; the magnet again draws on the keeper, the keeper again checks the descent of the carbon, and

so forth. Thus the points are retained at the right distance apart, and the light is continuous and brilliant. The lights thus produced are known as *arc lights*, and the apparatus in which they are produced are *arc lamps*.

The cost and inconvenience of producing electricity by means of the voltaic battery are so great as to quite preclude its use unless in very exceptional cases. But of late years vast improvements have been effected in dynamo-electric machines, which transform mechanical power into electricity in a very perfect manner, and yield it at a price which makes the electric light a formidable competitor with gas and other artificial lights for purposes of public and even of household illumination. For the latter purpose the current from such machines is conveyed by wires to a lamp such as that represented in fig. 542. These arc lights, however, are not adapted to household illumination, and are deficient in steadiness; they are best fitted for lighting large spaces, such as railway stations, docks, streets, and the like. What are called *incandescent lights*, though not so powerful, are best suited for indoor illumination, as the light is pleasanter, and is distributed from a number of centres. The principle on which these depend is that of allowing the current to traverse a thin thread of specially prepared carbon enclosed in a glass vessel from which the air has been exhausted. The ends of this carbon filament are suitably connected with wires, *a a′*, terminating in loops outside, which can be readily attached to the hooks *b b′*—the pressure exerted by the spring, R, insures good contact; these, in turn, lead to the binding screws, P, N, with which the wires conveying the current are connected. By means of the screw V, the support *c*

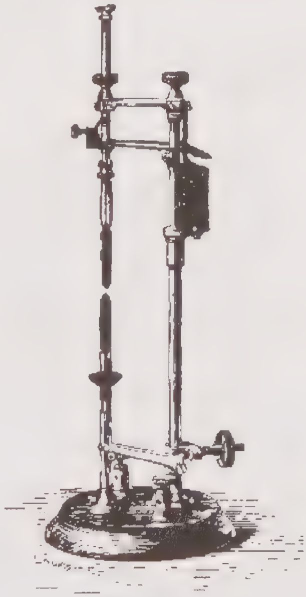


Fig. 542.

with its lamp can be attached to an upright stand, or to a bracket, like a gasalier. Carbon is chosen because it is infusible, which is not the case with any metal when traversed by a sufficiently powerful current. There are numerous forms of such incandescent lamps; that represented in fig. 543 was devised by Swan, of Newcastle, whose carbon thread is prepared by carbonising a special kind of cotton thread. Edison, of New York, uses bamboo in the construction of the carbon filament.

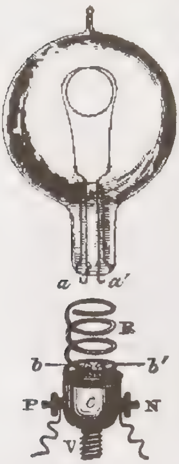


Fig. 543.

The filament in an incandescent lamp, after being in use for some time, becomes disintegrated and gives way; but a carefully constructed lamp will, with a moderate current, last for 1,000 hours. The intensity of the light depends upon and increases with the strength of the current—a lamp, for instance, which has an illuminating power of 16 candles (331) may have its luminosity doubled, or even more, by an increase in the strength of the current. This increase in luminosity is, however, purchased at the expense of the duration of the lamp; the more powerful the current, and therefore the luminosity, the shorter time does the lamp last.

A horse-power (286) employed in working the machine which produces the current will feed 12 lamps each of 16-candle power; the same power with an arc light will produce from five to ten times as much illuminating power.

512. **Chemical effects.**—These are among the most important of all the actions of the voltaic circuit. They consist of the separation and transport of the elements of the bodies traversed by the current. The first decomposition effected by the battery was that of water, obtained in 1800 by Carlisle and Nicholson by means of a voltaic pile. Water is rapidly decomposed by an applied E.M.F. of 4 or 5 volts (507); the apparatus (fig. 544) is very convenient for the purpose. It consists of a glass vessel fixed on a wooden base. In the bottom of the vessel two platinum electrodes are fitted, communicating by means of copper wires with the binding screws, *a* and *b*. The vessel is filled with water to which some sulphuric acid has been added to increase its conductivity. Pure water and pure sulphuric acid are very imperfect conductors, but a mixture of the two is a

tolerably good conductor. Two glass tubes filled with the acidulated water are inverted over the electrodes, and, on interposing the apparatus in the circuit of the battery, decomposition is rapidly set up, and gas-bubbles rise from the surface of each electrode. The volume of gas liberated at the negative electrode is about double that set free at the positive, and on examination the former gas is found to be hydrogen and the latter oxygen. This experiment accordingly gives at once the qualitative and quantitative analysis of water, for it shows that it consists of two parts by volume of hydrogen to one of oxygen.

In a circuit containing a water-decomposition apparatus, or *water voltameter* as it is called, V, Faraday introduced a tube, AB, containing tin chloride kept in a state of fusion by the heat of a spirit lamp (fig. 545). In the bottom of this a platinum wire was fused

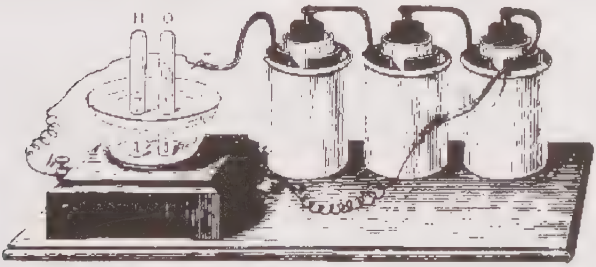


Fig. 544.

forming the negative electrode, while the positive electrode consisted of a rod of graphite ; when the current passed, chlorine was liberated at the positive, while tin collected at the negative electrode ; in like manner lead oxide was electrolysed, and yielded lead at the negative and oxygen at the positive electrode. Comparing the quantities of substances liberated, they are found to bear a certain definite relation to each other. Thus, for every 18 parts of water decomposed in the water voltameter there will be liberated 2 parts of hydrogen, 207 parts of lead, and 117 of tin at the respective negative electrodes, and 16 parts of oxygen and 71 (or $2 \times 35 \cdot 5$) parts of chlorine at the corresponding positive electrodes. Now these numbers are exactly as the chemical equivalents (not as the atomic weights) of the bodies.

It will further be found that in each of the cells of the battery

65 parts by weight of zinc have been dissolved for every two parts by weight of hydrogen liberated ; that is, that for every equivalent of a substance decomposed in the circuit one equivalent of zinc is

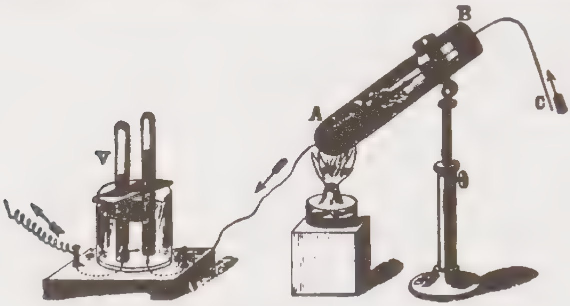


Fig. 545.

dissolved. This is the case whatever be the number of cells. An increase in the number only has the effect of overcoming the great resistance which many electrolytes offer, and of accelerating the decomposition. If in any of the cells more than 65 parts of zinc are dissolved for every two parts of hydrogen liberated in a water voltameter in the circuit, this arises from a disadvantageous local action ; and the more nearly the zinc in the battery approximates to the condition of pure zinc, the more exactly is the chemical relation between the products of decomposition realised.

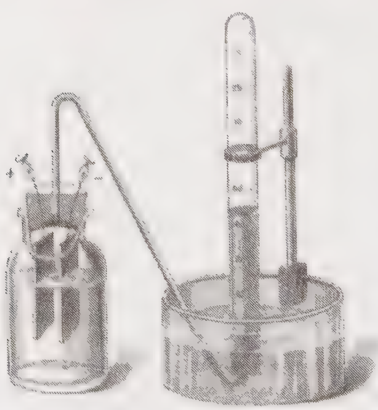


Fig. 546.

If the two platinum electrodes in fig. 544 are placed close together in acidulated water, the gases can be collected mixed instead of separately. Such a mixture of the two gases explodes and re-forms water with great violence

when a light is applied to it, or, when contained in a suitable vessel, an electric spark is passed through it ; this mixed gas is known as *detonating gas*. If it is collected in a graduated glass tube, it is found, in accordance with what has been stated, that currents of different strengths liberate the gas with varying rapidity ; the more powerful the current the more rapidly is the gas disengaged. The quantity liberated in a given time is proportional to, and is therefore a measure of, the quantity of electricity which has passed ; an apparatus based on this principle was devised by Faraday and called a *voltameter* (fig. 546).

By means of the voltameter we may conveniently illustrate the principles of the division of the electric current. Suppose that B (fig. 547) is a voltaic battery, and that V and V_1 are similar voltameters ; the current divides at c, and in the equal branches are placed two voltameters, v and v_1. If now the circuit is closed

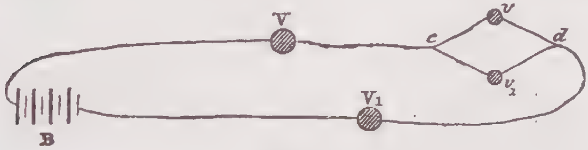


Fig. 547.

for a certain time, and the gas measured which is liberated in this time, it will be found that the volumes in V and V_1—that is, the voltameters in the *undivided* part of the circuit—are equal ; and that, if the resistances in the branches $c\ v\ d$ and $c\ v_1\ d$ are equal, the volumes of gas disengaged in them will also be equal to each other, but less than V or V_1, the sum of the volumes being, however, exactly equal to V or V_1 ; this will also be the case if the voltameters v and v_1 are not equal ; the sum will always be equal to V or V_1.

This may be expressed by saying that if two paths are open to a current it will divide itself as the conductivities in their branches, or, what is the same thing, inversely as the resistances. Thus, if the resistances of the two circuits v and v_1 are 1 and 4 respectively, then, of the current which divides between the points c and d, four-fifths will go through v and one-fifth through v_1.

When the current is passed through a solution of silver nitrate contained in a platinum dish, which serves as a negative electrode —the positive electrode being a silver rod held in a brass clamp—

metallic silver is deposited on the dish, and may be weighed (fig. 548). Such an arrangement is called a *silver voltameter*, and although more troublesome it is susceptible of greater accuracy. A current of an ampere (507) passing for an hour through such a solution will liberate 4·025 grammes of metallic silver; in like manner, a *copper voltameter*, with copper electrodes and copper sulphate solution, would give 1·181 gramme of metallic copper.

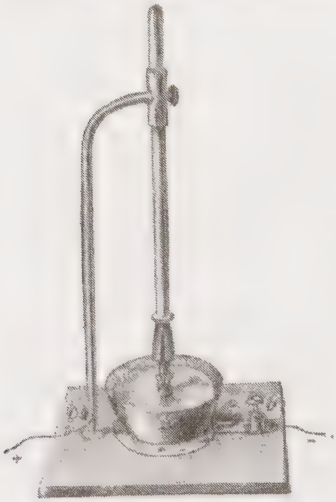


Fig. 548.

The weight of metal liberated from a solution of one of its salts in a second by unit current—that is to say, one ampere—is called the *electrochemical equivalent* of the metal. That of silver is 1·118 milligramme, and of copper 0·328 milligramme.

513. **Electrolysis.** — To those substances which, like water, are resolved into their elements by the voltaic current, the term *electrolyte* was applied by Faraday, to whom the principal discoveries in this subject, and also the nomenclature, are due. *Electrolysis* is decomposition produced by a voltaic current; the products of decomposition are called *ions*, that which is liberated at the positive electrode or *anode* being called the *anion*; that liberated at the negative electrode or *kathode*, the *kation*.

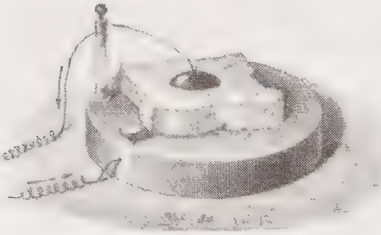


Fig. 549.

By means of the battery the compound nature of several substances which had previously been considered as elements has been discovered. With a battery of 250 cells, having an E.M.F. of

probably 150 volts, Davy, shortly after the discovery of the decomposition of water, succeeded in decomposing the alkalies potash and soda, and proved that they were the hydrated oxides of the hitherto unknown metals *potassium* and *sodium*. The decomposition of potash may be demonstrated with the aid of a battery of six volts electromotive force in the following manner: a small cavity is made in a piece of solid caustic potash, which is moistened, and a drop of mercury is placed in it (fig. 548). The potash is placed on a piece of platinum connected with the positive pole of the battery. The mercury is then touched with the negative pole. When the current passes, the potash is decomposed, oxygen is liberated at the positive electrode or anode, while the potassium liberated at the kathode amalgamates with the mercury. On distilling this amalgam out of contact with air, the mercury passes over, leaving the potassium.

The decomposition of binary compounds—that is, bodies containing two elements—is quite analogous to that of water and potash; one of the constituents goes to the anode and the other to the kathode. The bodies separated at the anode are called *electronegative* ions, because at the moment of separation they are considered to be charged with negative electricity, while those separated at the kathode are called *electropositive* ions. One and the same body may be electronegative or electropositive, according to the body with which it is associated. For instance, sulphur is electronegative towards hydrogen, but is electropositive towards oxygen. The various elements may be arranged in such a series that any one in combination is electronegative to any following, but electropositive towards all preceding ones. This is called the *electrochemical series*, and begins with oxygen as the most electronegative element, ending with potassium as the most electropositive.

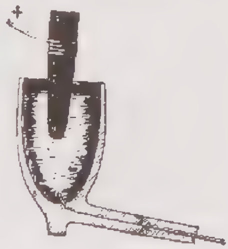


Fig. 550.

A very convenient arrangement for the preparation of metallic magnesium and some of the rarer metals consists of an ordinary clay tobacco-pipe (fig. 550), in the stem of which an iron wire is inserted just extending to the bowl, which is nearly filled with a mixture of the chlorides of potassium and magnesium. This is melted by a Bunsen burner, and a piece of graphite

connected by a wire with the positive pole of a battery is dipped in it, the wire in the stem forming the negative electrode. When the current passes, chlorine gas is liberated at the carbon electrode, while metallic magnesium collects about the end of the iron wire in the bowl.

514. **Electrotype.**—In the ordinary methods of reproducing statues, bas-reliefs, etc., in metal, moulds of baked clay or of sand are prepared, which are faithful hollow copies of these objects; then either melted iron or bronze is run into these; when the metal has solidified, an exact copy in relief is obtained of the object. In electrotypes, a mould of the object to be produced is required, but the reproduction is effected without either fusion or fire. An electric current quietly deposits a layer of metal of any desired thickness on a faithful impression of the object. This is the meaning of the term *galvanoplastics*, which is derived from the word 'galvanism,' and from a Greek word signifying 'to model.'

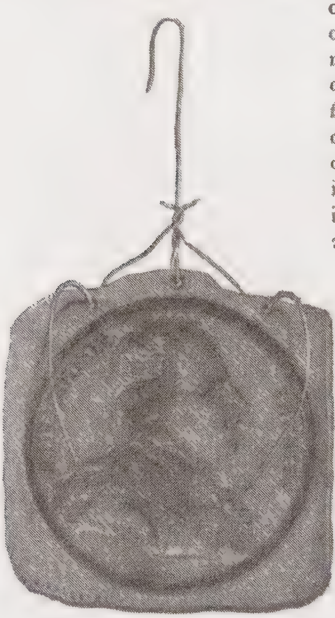


Fig. 551.

Fig. 552.

The practice of electrometallurgy consists of two distinct operations: first, the preparation of the mould or impression of the objects to be reproduced; and, secondly, the deposit of the metal

in this mould. The first process is the more delicate, and that on which mainly depends the success of the operation.

Various substances are used for taking impressions—wax, stearine, fusible metal, gutta-percha, etc. Of these the most useful, at any rate for small objects, is gutta-percha. This substance, which is hard at ordinary temperatures, softens when placed in warm water. When it has acquired the proper degree of softness, a plate of it is placed on the object to be copied and pressed against it. When the object is of metal—a medal, for instance—the gutta-percha is easily detached as soon as it is cold; but with a wood engraving or a plaster cast the gutta-percha adheres, and cannot be detached without danger of tearing. This may be remedied by previously brushing the mould over with blacklead, or *graphite*, as it ought to be called.

Suppose the subject to be reproduced is a medal (fig. 552); when the mould is obtained we have the medal hollow and inverted. It is now necessary to make its surface a conductor, for gutta-percha, being an insulator, could not transmit the current from the battery. This is effected by brushing it over very carefully with graphite (which is a good conductor) in all those places where the metal is to be deposited. Three copper wires are then fixed to it, one of which is merely a support, while the other two conduct the current to the metallic surface (fig. 551).

The mould is then ready for the metal to be deposited upon it; copper is ordinarily used, but silver and gold also deposit well.

In order to take a copper cast, a bath is filled with a saturated solution of copper sulphate, and two copper rods, B and A, are stretched across (fig. 553), one connected with the negative and the other with the positive pole of a couple of Daniell cells. From the rod connected with the negative poles, B, is suspended the mould, and from the other, A, a plate of copper, so that A forms the anode, B the kathode. The circuit being thus closed, the copper sulphate is decomposed, sulphuric acid is liberated at the anode, while copper is deposited at the kathode, on the mould suspended from the rod B, to which, indeed, several moulds may be attached.

The copper plate forming the anode serves a double purpose: it not only transmits the current, but it keeps the solution in a uniform state of concentration, for the acid liberated at A dissolves the copper, and reproduces a quantity of copper sulphate equal to

that which has been decomposed. The bath always remains, therefore, at the same degree of concentration—that is to say, always contains the same amount of salt in solution, which is a condition necessary for producing a uniform deposit.

An important industrial application is made of electrolysis in the *refining of copper*. The metal is extracted by the ordinary metallurgical processes so as to obtain plates containing 95 per cent. of pure copper, which are then used as positive electrodes in a bath of copper sulphate. The metal is deposited in a state of perfect purity on thin sheets of copper, which form the negative

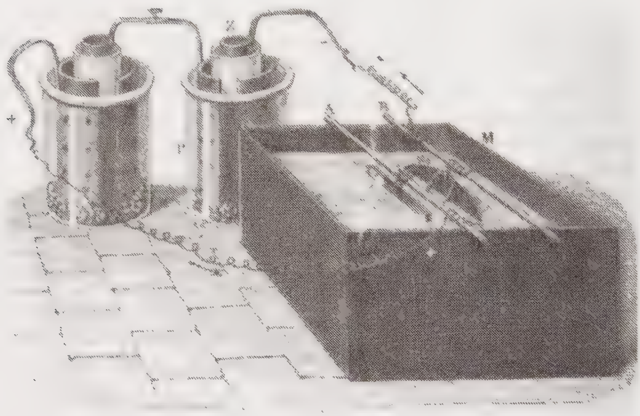


Fig. 553.

electrode, while the impurities fall to the bottom. As the electrodes are practically identical, there is no polarisation (497), and the work of the current is solely employed in overcoming the resistance of the baths. The application of electrolysis to the extraction of metals was of limited use until the powerful currents of dynamos (553) became available. In mountainous countries, where water-power can be had, it may in many cases be practicable to deal *in situ* with the extraction of metals from their ores.

515. **Electrogilding.**—The old method of gilding was by means of mercury. It was effected by an amalgam of gold and mercury, which was applied to the metal to be gilded. The objects thus covered were heated in a furnace, the mercury volatilised, and the

gold remained in a very thin layer on the objects. The same process was used for silvering ; but these methods were expensive and unhealthy, and have now been entirely replaced by electrogilding and electrosilvering. Brugnatelli, a pupil of Volta, appears to have been the first, in 1803, to observe that a body could be gilded by means of the battery and an alkaline solution of gold ; but De la Rive was the first who really used the battery in gilding. The methods both of gilding and silvering owe their present high state of perfection principally to the improvements of Elkington, Ruolz, and others.

The difference between electrogilding and electrosilvering and the processes described in the last paragraph is this—that, in the former, the metal is deposited on a mould in order to reproduce the objects given ; while, in the latter, the objects themselves are permanently covered with a very thin layer of gold or of silver.

The pieces to be coated have to undergo three preparatory operations.

The first consists in heating them so as to remove the fatty matter which has adhered to them in previous processes.

As the objects to be gilded are usually of copper, and their surface during the operation of heating becomes covered with a layer of suboxide or protoxide of copper, this is removed by the second operation. For this purpose the objects, while still hot, are immersed in very dilute nitric acid, where they remain until the oxide is removed. They are then rubbed with a hard brush, washed in distilled water, and dried in gently heated sawdust.

To remove all spots they must undergo the third process which consists in rapidly immersing them in ordinary nitric acid, and then in a mixture of nitric acid, bay salt, and soot. They are then well washed in distilled water, and dried as before in sawdust.

When thus prepared, the objects are attached to the negative pole of a battery of three or four cells, and if they are to be silvered they must be immersed in a bath of silver kept at a temperature of sixty to eighty degrees. They remain in the bath for a time which depends on the thickness of the required deposit. There is great variety in the composition of the bath. That most in use consists of two parts of cyanide of silver and two parts of cyanide of potassium, dissolved in 250 parts of water. In order to keep the bath in a state of concentration, a piece of silver forms the

positive electrode, which dissolves in proportion as the silver dissolved in the bath is deposited on the objects forming the kathode.

The processes of electrogilding are exactly like those of electrosilvering, with the exception that a bath of gold is used instead of one of silver, and the anode is a plate of gold. The bath used is a solution of cyanide of gold and cyanide of potassium.

The method which has just been described can be used not only for gilding copper, but also for silver, bronze, brass, German silver, etc. But other metals, such as iron, steel, zinc, tin, and lead, are very difficult to gild well. To obtain a good coating they must first be covered with a layer of copper, by means of the battery and a bath of copper sulphate; the copper with which they are coated is then gilded, as in the previous case.

When a solution of lead-oxide (litharge) in potash is electrolysed, the peroxide of lead liberated at the anode is deposited in extremely thin layers which exhibit colours like those of soap-bubbles, and serve thus for metallic coloration. The art of producing such deposits is known as *metallochromy*.

One of the most valuable applications of the electric deposition of metals is what is called the *steeling* (*aciérage*) of engraved copper plates. The bath required is prepared by suspending a large sheet of iron connected with the positive pole in a vessel filled with a solution of sal-ammoniac, while a thin strip of iron is connected with the negative pole. By this means iron from the large plate is dissolved in the sal-ammoniac, while hydrogen is given off from the small one. When the bath has thus taken up a sufficient quantity of iron, an engraved copper plate is substituted for the small strip. A bright deposit of iron begins to form at once, and the plate assumes the colour of a polished steel plate. The deposit thus obtained in the course of half an hour is exceedingly thin, but is extraordinarily hard, so that a far larger number of impressions can be taken from a plate thus prepared than from a plate of ordinary copper.

Another application which is rapidly extending is that of coating metals with *nickel* or *cobalt*. These form a very hard coating which protects softer metals from mechanical injury. Nickel gives a bright coating like silver, which, however, does not tarnish as silver does. Cobalt gives a coating of a reddish hue.

516. **Secondary cells, accumulators.**—The chemical decompositions effected by the passage of the current (512) put into our

hands a means of *storing* or *accumulating* electricity. For when two plates of platinum placed in dilute sulphuric acid are connected with the poles of a cell, and are then detached from the battery and connected with any arrangement for showing the passage of the electric current, it will be seen that such a current is produced, but its direction is opposed to that of the original current. This may be illustrated by an arrangement represented in fig. 554, in which B is a constant cell, V a voltameter (512), G a galvanometer (521), and H a mercury cup. The wire L being disconnected from H, a current is produced in the voltameter, the direction of which is from P to P′ ; if now the wire F be detached from H, and L be connected therewith, a current is produced through the galvanometer, the direction of which is from P′ to P ; that is, the opposite of that which the element had previously produced. The current thus produced is due to the *polarisation of the electrodes.* By the passage of the current the ultimate products of chemical decomposition—in the above case oxygen and hydrogen—are accumulated on the two electrodes, so that when the plates are disconnected from the battery the gases are in a condition in which they can readily unite with each other, and by their union re-form water. Thus it is not an accumulation of electricity, in the ordinary sense of the word, which is here produced, but a storage of chemical energy, which can be converted into electric energy by the reunion of the separated ions.

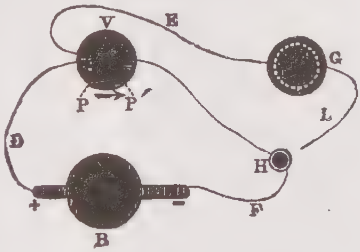


Fig. 554.

Planté was the first to use lead plates immersed in dilute sulphuric acid in the construction of storage batteries. Each cell consists of two lead plates rolled in a spiral and separated by strips of felt or other non-conductor. The general nature of the action of charging an accumulator is that the oxygen liberated at the anode converts the surface into peroxide of lead (*brown or puce oxide*), while hydrogen is set free at the kathode ; when the charging current is reversed, the peroxide is reduced to metallic lead, which, however, is in a spongy state, while the other plate is now covered with brown peroxide. By repeating this process, with currents

alternately in opposite directions, both plates ultimately acquire this spongy texture, which enables much more of the peroxide to be formed and thereby renders the cell more powerful. Finally, the cell is charged, so that one plate is practically lead peroxide and the other metallic lead, and it can now be used as an independent source of electricity. The metallic lead plate corresponds to the zinc, and the peroxide plate to the copper, of an ordinary primary battery, but there is no polarisation, as the hydrogen is spent in deoxidising the peroxide. As the action goes on, the lead plate is oxidised into protoxide of lead and the peroxide is reduced to the same condition, and when both plates are alike the action ceases. But the cell may be restored to its original active condition by recharging from a dynamo or otherwise. The E.M.F. of this cell is about two volts, and as the lead plates are of large area and very close together, the internal resistance is much less than that of any primary cell of the same size.

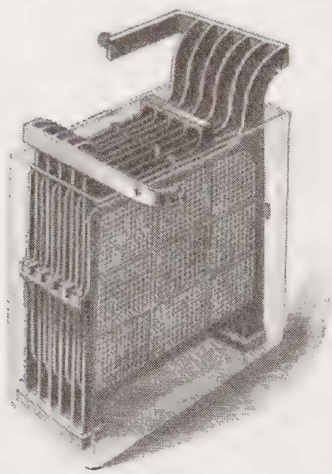


Fig. 555.

The storage cells now so largely used for electric lighting, traction, and other purposes, differ from Planté's in details of construction, but are based on the same general principles. The tedious operation of *forming* the cells by passing successive currents in opposite directions between the plates is now to a large extent dispensed with. Each plate consists of a lead grid (fig. 555), the spaces in which are filled with a mixture of oxides of lead formed into a paste, the positive plates being thicker and containing a larger quantity of active oxide than the others.

Fig. 555 shows one of the storage batteries of the Electric Power Storage Company ; it will be seen that the whole of one set of six plates forming the negative electrode are fitted together, and a corresponding set of five plates, also joined together, can be placed between the other set, being kept from touching each other

by staples or studs of some insulating material. Each set of plates forms in effect a single large one, which is thus placed with its coated face opposite the coated faces of the other plates. The object in storage cells is to increase the surface and lessen the weight as far as practicable, and also, by bringing the plates near each other, to diminish the internal resistance. A given number of such cells may by suitable commutators be combined so as to produce at will the effects of high potential or of quantity.

The electromotive force of a storage cell on discharge is a little over 2 volts; if the cell is discharged immediately after being charged it rapidly falls to 2 volts, at which it remains pretty constant, falling very slowly to 1·85 to 1·8 volt, after which it falls off rapidly again until the charge is exhausted. It is found best not to let the discharge fall much below 2 volts, as this is prejudicial to the durability of the cell.

The *capacity* of a storage cell is stated in *ampere-hours*; for example, a cell whose capacity is 80 ampere-hours will provide a current of 1 ampere for 80 hours, 4 amperes for 20 hours, and so on.

The efficiency of an accumulator is the ratio between the electric energy available in the discharge and the energy absorbed in the charge. The efficiency of modern accumulators of the best construction is about 80 per cent.

In accumulators which are to be used for driving the motors of tramcars or electric launches, the capacity is of first importance, while in the case of stationary accumulators, as in electric lighting, the efficiency is the chief point.

CHAPTER IX

RELATION BETWEEN ELECTRICITY AND MAGNETISM

517. **Resemblance and dissimilarity.**—Early in the history of the two sciences, the analogy was remarked which existed between the phenomena of electricity and magnetism. It was observed that like kinds of electricity repelled each other, as also did like kinds of magnetism, and that unlike kinds attracted. It had, moreover, been observed that lightning, in striking a ship, often reversed the polarity of compass-needles, and even sometimes robbed them of all magnetic power. But though there are many points of resemblance between electricity and magnetism, the dissimilarities are numerous. For instance, magnetic properties cannot be transmitted to good conductors, as can electric properties. A magnet placed in contact with the earth does not lose its magnetism as an electrified body loses its electric charge. Again, electricity can be produced in all bodies, while magnetism is only manifested by a very small number. Among these resemblances and dissimilarities, nothing could be affirmed respecting any definite relation between electricity and magnetism until towards the end of 1819, when Oersted, professor of physics in Copenhagen, made a memorable discovery, which for ever intimately connected these two physical agents. Thus arose a new branch of science called *electromagnetism*, to express that the phenomena are at once magnetic and electric.

518. **Action of currents upon magnets.**—The fact which Oersted discovered was the directive action of currents upon magnets. He found that *electric currents have a directive action upon the magnetic needle, and always tend to set it at right angles to their own direction.*

To verify this action of currents upon magnets, the experiment is arranged as shown in fig. 556. A magnetic needle, AB, movable upon a pivot, being at rest in the direction of the magnetic

meridian, a wire parallel to the meridian is held over it and a current is allowed to pass through the wire. The needle is then seen to deviate from its position of rest, oscillate, and ultimately come to rest in a position inclined to the magnetic meridian ; the deviation from the meridian being greater the closer the wire to the needle and the stronger the current.

In this experiment the direction in which the needle is deflected varies with the direction of the current ; if the current goes from south to north above the needle, the north pole is deflected to the west ; if, on the contrary, it goes from north to south but still above the needle, the north pole is deflected to the east. When

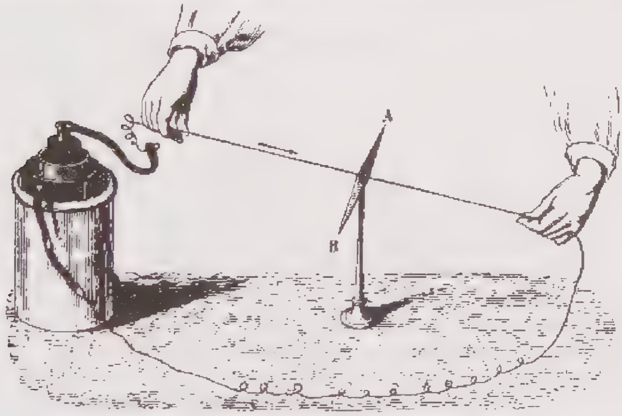


Fig. 556.

the current passes below the needle, the same phenomena are reproduced, but in exactly the reverse order. All these different cases were reduced to a single one by Ampère.

519. **Ampère's rule.**—Ampère gave the following *memoria technica*, by which all the various directions of the needle under the influence of a current may be remembered. If we imagine an observer placed in the wire in such a manner that the current entering by his feet issues by his head, and that his face is always turned towards the needle, we shall see that in the above four positions the north pole is always deflected towards his left hand. By thus personifying the current, the different cases may be comprised within this general principle : *In the directive*

action of currents on magnets, the north pole is always deflected towards the left of the current.

520. **Magnetic field due to a current.**—The fact discovered by Oersted is a particular case of the general principle that an electric current is always accompanied by a magnetic field all round it. In the case of a linear conductor the lines of force in the field are circles in planes perpendicular to the current, having their centres in the axis of the wire. The existence of the field may be shown by a vertical wire forming part of an electric circuit which passes at right angles through a piece of cardboard or thin wood. When iron filings are sprinkled on the cardboard they are seen to arrange themselves—when the cardboard is tapped—in circles as represented in fig. 557. If the direction of the current in the wire, xy, is that shown by the arrow, the direction of the lines (*i.e.* the direction in which a free north pole would move) is to the left of an observer swimming with the current. The direction of the particles of iron is that which very small magnets would have if placed there.

Fig. 557.

When a copper wire through which a fairly strong current is flowing is dipped into iron filings, the filings cling to it all round

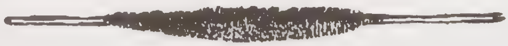


Fig. 558.

(fig. 558), each particle setting itself perpendicular to the wire; they become detached as soon as the circuit is broken, and there is no action on any non-magnetic metal.

The fact and direction of the magnetic field in the neighbourhood of a straight conductor may be shown also by the apparatus of fig. 559. NS is a bent magnet, pivoted at p, so as to turn about a vertical axis. In the bend is a cup of mercury, m, in conducting connection with the maget, while tt is a circular trough of mercury always in contact with the magnet by the arm, a. The

lower end of a vertical copper wire, *c*, dips into the mercury, *m*, its upper end, as well as the mercury in *tt*, being connected with a battery. When the circuit is completed the magnet pole, N, rotates round the wire in the anticlockwise direction if the current flows up the wire as represented in the figure. If the current is reversed, the direction of rotation will be reversed.

In the case of a bent wire the lines of force due to the passage of a current, instead of being exact circles, will be more or less deformed. If the current flows in a circular ring, the system of lines of force will be as shown in fig. 560, in which *a a′* are sections of the ring made by the plane of the paper. The current is supposed to

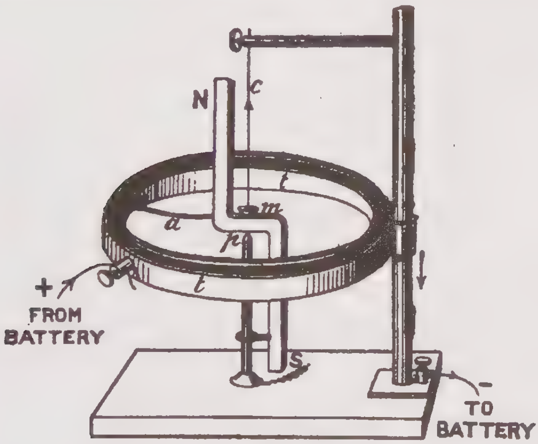


Fig. 559.

come up from below at *a′* and pass down through the plane of the paper at *a*. Near the centre of the ring the lines are straight and parallel. Close to the circumference they are nearly circular. Each line of force is a closed curve threading the ring.

521. The name *galvanometer* or *multiplier* is given to an instrument by which the existence, direction, and strength of an electric current may be determined. It was invented by Schweigger, in Germany, a short time after Oersted's discovery.

In order to understand its principle, let us suppose a magnetic needle, *ab*, suspended by a silk thread (fig. 561), and surrounded, in the plane of the magnetic meridian, by a copper wire forming a

complete circuit round the needle in the direction of its length. When this wire is traversed by a current, it follows, from what has been said (518), that in every part of the circuit an observer lying in the wire in the direction of the arrows, and looking at the needle, *ab*, would have his left always turned towards the same point of the horizon, and consequently that the action of the current in every part would tend to turn the north pole in the same direction—that is to say, that the actions of the four branches of the circuit concur to give the north pole the same direction. By coiling the copper wire in the direction of the needle, as represented in the figure, the action of the current has been *multiplied*. If, instead of a single turn of wire, there are several, provided they are insulated, the action becomes still more multiplied, and the deflection of the needle increases—or, what is the same thing, a much feebler current is required to produce a given deflection.

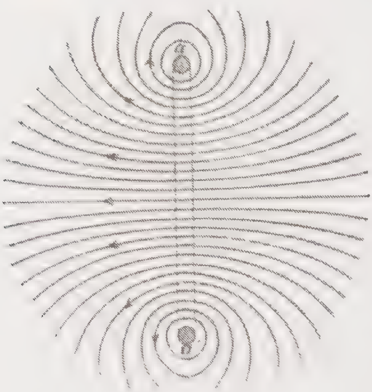


Fig. 560.

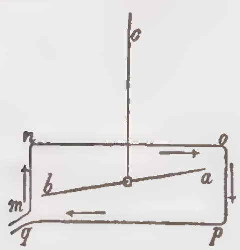


Fig. 561.

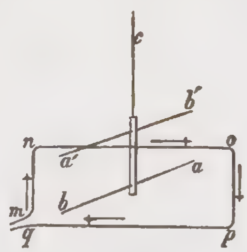


Fig. 562.

As the directive action of the earth continually tends to kee the needle in the magnetic meridian, while the current tends to place it at right angles to this direction, the needle will take up a position inclined to the meridian at an angle which is greater the

less the earth's action on the needle. This action may be diminished by using an astatic system of two needles, as shown in fig. 562. An astatic system consists of two needles rigidly connected together, with equal magnetic moments (418), parallel magnetic axes, and opposite poles in the same direction. The earth's magnetism acts equally but oppositely on the two needles, so that, if the conditions of astaticism were exactly realised, the system would rest in *any* direction. But if the magnetic moment of one of the needles is slightly greater than that of the other, the system will come to rest in the magnetic meridian, the directive action of the earth on it being equal to the difference of its actions on the two needles separately. The action of the earth on the system is consequently very feeble, and, further, the actions of the current on the two needles become accumulated. In fact, the action of the circuit, from the direction of the current indicated by the arrows, tends to deflect the north pole, *a*, of the lower needle, *ab*, towards the west. The upper needle, *a′b′*, is subjected to the action of two contrary currents, *no* and *qp*; but as the first, *no*, is nearer, its action preponderates. Now, this current *no*, passing below the needle, evidently tends to turn the north pole *a′* towards the east, and consequently the pole *b′* towards the west—that is to say, in the same direction as the pole *a* of the other needle. Looking at the matter otherwise, we may say that the lines of force due to the current thread through the rectangle *n*, *o*, *p*, *q*, passing inside it from the front to the back of the paper, and outside it from the back to the front. Thus the north poles *a* and *a′* are urged in opposite directions.

From these principles it will be easy to understand the explanation of the astatic needle galvanometer. The apparatus represented in fig. 563 consists of a thick brass plate resting on levelling screws; on this is a copper frame on which is coiled a great number of turns of wire covered with silk. The two ends terminate in binding screws, *n* and *m*. Above the frame is a graduated circle, with a central slit parallel to the direction in which the wire is coiled. By means of a fine filament of silk, an astatic system is suspended; it consists of two needles, *ab* and *a′b′* (fig. 562), one above the scale, and the other within the bobbin of wire.

For use the instrument is so adjusted that the needles, and also the slit, are in the magnetic meridian, and that the upper needle points to the zero of the scale.

To show, by means of the galvanometer, the electricity developed

in chemical actions—for instance, in the action of acids on metals—two platinum wires may be attached to the binding screws, *m* and *n*. One of them is then plunged in very dilute sulphuric acid, and the other placed in contact with a piece of zinc held in the hand, which is dipped in the liquid (fig. 563). An immediate deflection is observed, which indicates the existence of a current; and, from the direction which the north pole of each needle assumes, it is seen that the direction of the current is that indicated by the arrows.

For certain kinds of experiments it is desirable that the galvanometer should have a very large number of turns of wire,

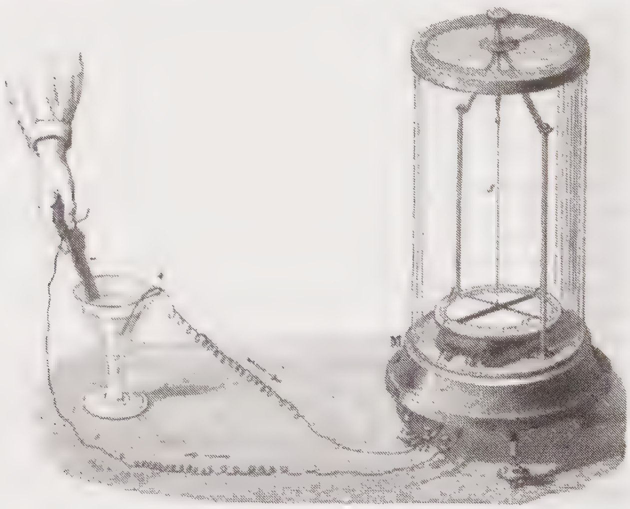


Fig. 563.

say from 20,000 to 50,000, *i.e.* that its resistance should be large. Such galvanometers are called *long-coil galvanometers*. A *short-coil galvanometer* is one with a few turns of tolerably thick wire; such a one would be used in a thermoelectric circuit (564).

522. **Tangent galvanometer.**—This is a form of galvanometer specially suited for measuring the strength of currents. It consists of a small number of turns of stout wire, or even of a single turn, forming a ring of 8 or 10 inches in diameter (G, fig. 568). In the centre is suspended a small magnetic needle not more than

about ·75 of an inch in length, playing over a graduated scale, by which the deflection can be measured; as this is difficult with so small a needle, it is provided with a long light index.

If the ring is placed in the magnetic meridian, and different currents are allowed to pass round the ring or coil, it will be found that the magnetic needle is deflected to varying extents; and it can be proved that the strengths of the various currents are proportional, not to the angles of deflection themselves, but to the trigonometrical *tangents* of such angles; and it is from this property that the name of the apparatus is derived. Thus, if the angles observed in three different cases are 30°, 45°, and 60°, the corresponding strength of currents will be as tan 30° : tan 45° : tan 60°, or, as ·58 : 1 : 1·73.

523. **D'Arsonval's galvanometer.**—In this instrument the principle of the preceding ones is reversed; the magnet is fixed, while the existence and direction of the current are indicated by the motion of the coil of wire in which the current itself flows.

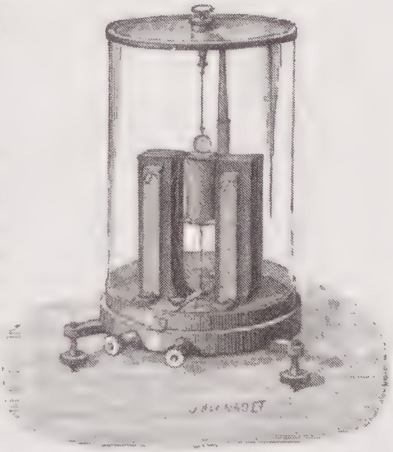


Fig. 564.

Between the poles of a powerful horseshoe magnet (fig. 564) an insulated rectangular coil of wire of many turns is suspended; one end of the coil is attached to the wire by which the coil is suspended, while the lower end is connected with a metal strip in connection with a binding screw; the rod by which the frame is supported is also connected with a binding screw.

Inside the movable coil is an iron cylinder—supported by the metal rod—which strengthens the magnetic field. When the current passes, the coil tends to set at right angles to the line joining the poles, and for small angles the current is proportional to the angle of deflection; this is read off by means of the light of a lamp reflected on a scale from a light mirror attached to the

coil, a mode of observation of great delicacy and accuracy, and much used in physical measurements. When the terminals are connected to a circuit the galvanometer is almost *dead-beat*—that is to say, the coil sets almost immediately in its final position.

The instrument itself is based on an apparatus devised by Lord Kelvin (at that time Prof. W. Thomson) for telegraphing through the Atlantic cable.

524. **Ohm's law.**—We have already seen that in a complete voltaic circuit there is always a certain force at work, to which is due the production of electric effects in the circuit, and to which the term *electromotive force* (507) is applied. Now, any circuit is made up of various materials : the metals themselves, the exciting liquid, the wires, and the apparatus used to detect or measure the strength of the current or to demonstrate its effects. No substance whatever is a perfect conductor ; all offer a certain obstacle or *resistance* to the passage of the electricity (507), and this resistance varies greatly according to the dimensions of the materials and their special nature. Th strength of current produced by any given combination depends on the ratio of these two factors ; it is directly proportional to the electromotive force, and is inversely proportional to the resistance, so that with a given electromotive force the current is stronger the smaller the resistance, and, conversely, with a fixed resistance the current is stronger the greater the electromotive force. The principle known as *Ohm's law* states that the strength of a current (in amperes) is equal to a fraction, the numerator of which is the E.M.F. of the battery (in volts) and the denominator the total resistance of the circuit (in ohms).

In voltaic combinations a distinction is drawn between the *internal* and the *external* resistance, the former being that which is offered by the liquid between the plates, while the external resistance includes the joining wires and the whole of the apparatus in which the electric effects are to be produced.

In a voltaic cell which is to have a low internal resistance, the plates should be large, and should be close together in the liquid.

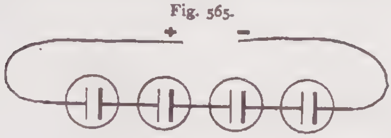
If we have four cells, we may arrange them in a battery so that the zinc of one is joined to the copper of the next, the zinc of this to the copper of the third, and so on ; this is the arrangement in *series*, and is represented in fig. 565 ; this gives a battery with four times the electromotive force and also four times the resistance of a single cell. Or the four cells may be arranged *abreast* or *in parallel* (fig. 566) where all the zincs are joined together and

all the coppers ; the effect is to produce a single cell of four times the size, and therefore of one-fourth the internal resistance (507), but of no greater electromotive force ; for the E.M.F. only depends on the nature, and not at all on the dimensions, of the metals (507). We may further arrange them so that two cells are joined in parallel forming a single cell of double the size, and then two of these double cells are joined in series (fig. 567).

If we have twelve cells, the student will see that he can arrange them in six different ways.

If each of the twelve cells has an E.M.F. of 1 volt and an internal resistance of 1 ohm, and if the external resistance is 20 ohms, then if the cells are in series the total E.M.F. is 12 volts, and the total

Fig. 565.



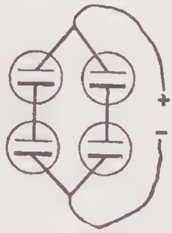


Fig. 567.

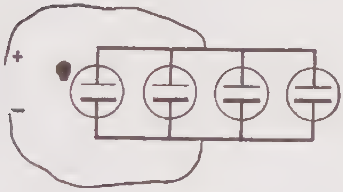


Fig. 566.

resistance $20 + 12 = 32$ ohms ; hence the strength of the current is $\frac{12}{32} = \frac{3}{8}$ ampere. If the cells are arranged all in parallel, the resistance of the battery is $\frac{1}{12}$ ohm, and therefore the total resistance $20 + \frac{1}{12} = \frac{241}{12}$ ohms. The E.M.F. being in this case 1 volt, the strength of the current is $\frac{12}{241}$ ampere The current strengths in each of the other possible modes of arranging the twelve cells may easily be calculated.

Simple calculations based on Ohm's law enabl us to tell what, with a given number of cells and a given external resistance, is the best way of arranging them so as to produce the maximum effect. If the external resistance is great, as with a long length of telegraph wire, the cells should be arranged in series ; if, on the contrary, it is small, such as a short thick magnetising spiral or

an electrolytic tank, the cells should be arranged in parallel. The general principle is that the best result is obtained when the total internal resistance of the battery is, as nearly as it can be made, equal to the total external resistance.

525. **Laws of electric resistance.**—We shall make use of the tangent galvanometer (522) to demonstrate the laws of electric resistance, a matter of great importance both from the practical and also from the theoretical point of view. Suppose we connect a constant cell, B (498), with the binding screws of a tangent galvanometer, G, in the manner represented in fig. 568, in which C and C′ are two mercury cups, which enable us readily to introduce into the circuit wires of different materials and dimensions. If, in the first case, the coiled wire, R, represents a short length of the same

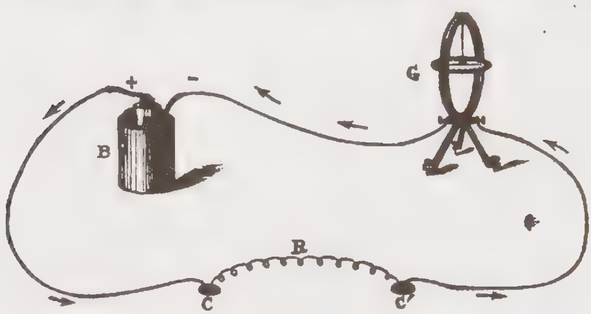


Fig. 568.

wire as the connecting wires, which are usually copper, the needle of the galvanometer will be deflected through a certain angle, and the tangent of this angle is a measure of the strength of the current.

Suppose now a greater length of the same wire be interposed: the angle of deflection will be smaller, showing that the current is weaker; and by the introduction of a still greater length it will be still more enfeebled. Hence, other things being equal, the current is weaker when it has to traverse a greater length of a given conductor, or the *resistance of a body increases with its length.*

If now we substitute for the original wire, R, another wire of the same length and the same material, but of smaller diameter, the current is weaker; and by taking a still thinner wire it is again

more enfeebled. On the contrary, if the same length of wire, of the same material but of greater diameter, be introduced, the current is stronger. Hence ***the smaller the section of a conductor, the greater is the resistance.***

Again, if for the original copper wire we take a wire of the same length and the same diameter, but of some different material, such as iron, we shall find that the current is weaker; and if the wire

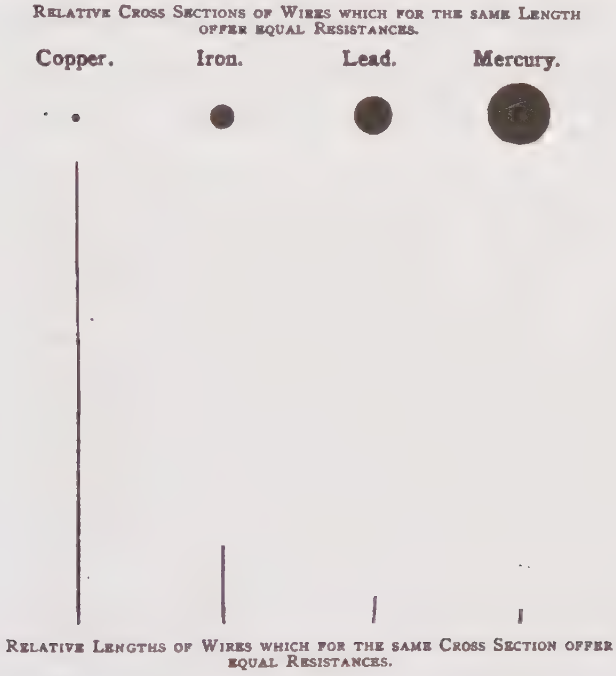


Fig. 569.

be of German silver or of lead, it is still more enfeebled, showing that ***the resistance of a body depends on its specific nature.***

Continuing and varying these experiments, we arrive at the following general law: ***the resistance of any body is directly proportional to its length, and is inversely proportional to its cross section and to its conductive power.***

Of all substances in ordinary use, copper, when pure, is by far the best conductor ; silver has only a slight advantage over copper in respect of electric conductivity. Fig. 569 represents the relations of a few of the metals in this respect.

The quality of a metal has a great influence on its conducting power ; the presence in copper of minute traces of certain substances, which it would be difficult to determine by chemical methods, greatly diminishes its conductivity, or, what is the same thing, increases its resistance. This is very important in the wires used in long lines of telegraph communication, more especially in the submarine cables (540). An impurity in the wire, which has the effect of reducing its conductivity, would have the same effect as if the current had to traverse an additional number of miles of the wire.

Those metals which have high conducting power for heat are those also which are good conductors of electricity.

The resistance of liquids is much greater than that of metals ; thus, dilute sulphuric acid, which has the highest conductivity of all liquids, has about a million times as great a resistance as copper.

The resistance of a body varies with the temperature ; that of metals increases with the temperature ; for instance, iron at a white heat has seven times as great a resistance as at the ordinary temperature. That of liquids, on the contrary, is diminished. Hence it is that the resistance of batteries is diminished after they have been in action for a while ; for whenever the circuit is closed, heat is produced in all parts of it, including the liquids, and thus the internal resistance is lessened. The insulation resistance of non-conductors such as india-rubber, gutta-percha, glass, etc., diminishes as the temperature rises.

526. **Shunts.**—We may here describe the action of a ***shunt.*** Imagine a voltaic circuit made up of a battery, conducting wires and a galvanometer, and that the resistance of the battery is 2 ohms, that of the conducting wires or *leads* 1 ohm, and the resistance of the galvanometer is 100 ohms. Let the electromotive force of the battery be E, to which for our present purpose we need assign no numerical value. Then, according to Ohm's law (524), the current will be $\frac{E}{2+1+100} = \frac{E}{103}$.

Suppose now that a wire, *s*, having a resistance of one ohm, is joined at the points *a c* (fig. 570), a portion of the current will

be *shunted* through s: the current which divides will do so in the proportion of 100 to 1 (512)—that is, 100 parts will pass through the shunt, and one part through the galvanometer. Now by adding the shunt the value of the primitive current is altered. The resistance of any two conductors joined *in parallel*, as it is termed, is equal to the product of the two divided by their sum; in this case it is $\frac{100 \times 1}{101}$, or virtually unity. So that the current which was $\frac{E}{101}$ is now $\frac{E}{2 + 1 + 1} = \frac{E}{4}$. But of this increased current $\frac{1}{101}$th part only passes through the galvanometer—that is, the current in it is $\frac{E}{404}$, or practically one quarter what it was before.

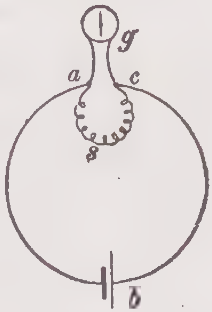


Fig. 570.

Galvanometers are often provided with resistance-boxes (527) arranged as shunts, so that any given portion of the current may be passed through the galvanometer. It is thus possible to use very delicate galvanometers for measuring even powerful currents.

527. **Electric units.**—It is perhaps one of the most characteristic features of the modern progress of electricity that, not only for purely scientific purposes, but also for the most ordinary practical applications, the quantities of electricity concerned can be determined with as great accuracy as can any weighing and measuring in daily life. All electric measurements may be expressed by reference to certain fundamental standards, just as in ordinary life we have certain standards of weight and length. In an elementary work it is not practicable to give any adequate, and yet brief, account of the scientific basis of this system of electric measurements, and we may content ourselves with adopting and using them, just as we use the pound as standard of weight and the foot as measure of length, without entering into the reasons which have led to the adoption of these standards.

It has already been pointed out (507) that three of the standard electric units—viz. those of resistance, electromotive force, and current strength—are called respectively an *ohm*, a *volt*, and an *ampere*. The *ohm*, which is defined by reference

to a column of mercury (507), is usually represented by a certain length of wire of a definite material and diameter. Such a length of wire is called a *resistance-coil*, and is usually employed in a *resistance-box*. Fig. 571 represents the way in which several such coils are arranged in the inside of a box. Each coil consists of a certain length of insulated wire, representing a definite resistance and wound double; the ends are connected to solid pieces of brass. These pieces are not in contact, but can be connected by the insertion of brass plugs.

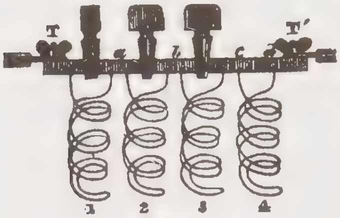


Fig. 571.

If the terminals of a circuit are connected with TT′ (fig. 571) and all the plugs are inserted, the resistance-box offers no appreciable resistance, for the current passes by the plugs and the massive metal; but by the removal of any of the plugs the current has to pass through the wire coil between the two brass pieces, and thus its resistance is introduced into the circuit. In the case represented in the figure the current has to traverse a resistance of 4 ohms.

The coils are in multiples and submultiples of ohms, and are so arranged that their combination may be as greatly varied with as few resistances as possible. Thus, a set of eleven coils of 0·1, 0·2, 0·2, 0·5, 2, 2, 5, 10, 10, 20, and 50 enables us to introduce any resistance from 0·1 to 100 into the circuit.

A form of resistance much in use for technical purposes is represented in fig. 572. The spiral wires are of German silver, and the straight ones are stout copper wires which offer no appreciable resistance, both being connected with studs on a frame of insulating material. The terminals are at *k* and *k*, the one on the right being connected with a metal spring having an insulating handle. This can be moved backwards and forwards, and thus be placed in contact with any of the studs with which the resistances are connected. In this way, as an examination of the figure will show, any number of resistances from 1 to 10 may be brought into the circuit, the spring being so wide that continuity is never broken.

A mile of No. 8 iron telegraph wire, the diameter of which is

$\frac{1}{8}$ of an inch, has a resistance of about 14 ohms. One hundred yards of hoop iron, half an inch in breadth, and one thirty-second of an inch in thickness, has a resistance of one ohm.

A resistance of one million ohms is called a *megohm*, and a resistance equal to the millionth part of an ohm is a *microhm*.

The electromotive forces, in volts, of some of the more common cells have been already given (507).

The *Ampere*, or unit of strength of current, is defined from Ohm's law (524) as being that current which would be produced by an electromotive force of a volt acting in a circuit through a resistance of an ohm; or, for instance, what is the same, an E.M.F. of 10 volts through a resistance of 10 ohms. A *milliampere* is the $\frac{1}{1000}$ of an ampere. The currents in ordinary use for electric lighting have a strength of from 10 to 70 amperes or even more; those in working the telegraph from 14 to 16 milliamperes. An ordinary-sized Daniell's element with an internal resistance of 1·3 will give a current of 0·8 ampere when put on *short circuit*, or *short-circuited* as it is technically called; that is to say, when its poles are joined by a wire which has no appreciable resistance. In like manner a Bunsen's element, whose internal resistance is $\frac{1}{10}$ of an ohm, in the same condition will produce a current of 18 amperes.

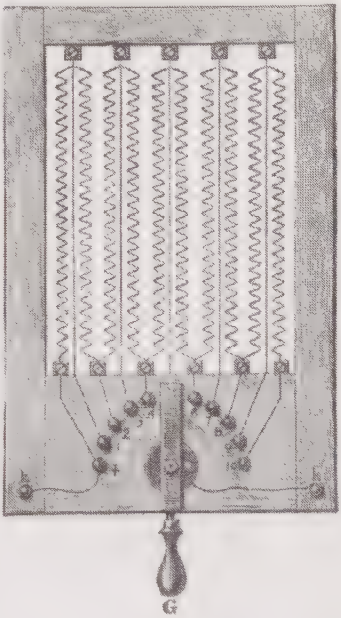


Fig. 572.

The *Coulomb* is the unit of quantity of electricity; it is that quantity which flows in a second of time through a circuit which has a resistance of an ohm with an electromotive force of a volt; or, in other words, it is that quantity which passes in one second with a current of an ampere.

The *Voltcoulomb*, or unit of *electric work*, is the work done when a coulomb of electricity falls through a difference of potential of a volt; it is precisely analogous to the foot-pound or unit of mechanical work (286), and is known as the *Joule*.

When this amount of electric work is done in one second, we have the unit of *electric power* or activity; it is the effect produced when a coulomb of electricity passes in a second of time under an electromotive force of one volt; in other words, it is the rate of expenditure of energy when there is a current of one ampere under an electromotive force of one volt. This *Voltampere*, or unit of electric power, is usually known as the *Watt*. A horse-power is equal to 746 watts, or one watt is $\frac{1}{746}$ of a horse-power, or, what is the same, to 0·74 foot-pound (286) or 0·102 kilogrammetre. That is to say, that the amount of mechanical work represented by 0·74 of a foot-pound, if it could be converted into electricity without loss, would produce for one second a current of an ampere under an E.M.F. of one volt.

A *Kilowatt*, or Board of Trade unit, is 1,000 watts, and is equal to 1·34 horse-power.

The important industrial applications of electricity have led to the invention of *amperemeters* or *ammeters*, instruments by which the strength of a current in *amperes* may be directly read off. The amperemeter or ammeter is essentially a galvanometer in which the motion of the needle is controlled by a spring or by being placed in a powerful magnetic field. The instrument is graduated empirically by passing through it currents of known strength, which may be determined by a copper or silver voltameter (512), and noting the corresponding positions of the needle.

The *Voltmeter*, which is not to be confounded with the *voltameter* (512), is also a special form of galvanometer by which the difference of potentials or number of volts between any two parts of a circuit can be indicated by a simple reading. The coil is of long fine wire, offering so great a resistance that it can be interposed as a shunt in the circuit without appreciably altering the strength of the current. It also is graduated empirically by noting on a scale the deflection of the needle when the ends of the wire are exposed to various known differences of potential.

CHAPTER X

ELECTRODYNAMICS

528. **Action of currents on currents.**—Ampère was led by experiment to the important discovery that electric currents act on each other as do magnets ; and out of this has arisen a special branch of physics, to which the name *electrodynamics* has been given. The actions which currents exert on each other are different according as they are parallel or angular.

I. *Two currents that are parallel, but in contrary directions, repel each other.*

II. *Two currents, parallel and in the same direction, attract each other.*

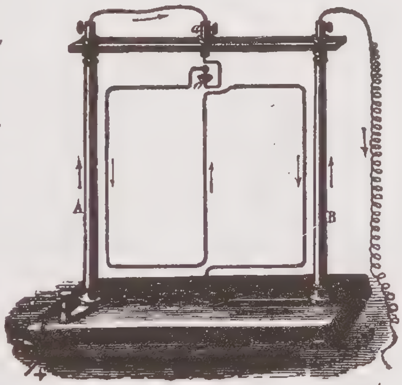


Fig. 573.

To verify these laws use may be made of the apparatus represented in fig. 573. On a wooden base are fixed two brass columns, A and B, joined at the top by a wooden cross-piece. In the centre of this is a brass binding screw, *a*, and below this a mercury cup, *o*. In this is placed an iron pivot attached to the end of a copper wire which is bent in the manner represented in the figure, and terminates in a mercury cup, C, on the base of the apparatus. It thus forms a circuit movable about the pivot.

This being premised, the circuit is arranged in the plane of the two columns, as shown in fig. 573 ; the positive pole of a voltaic battery is connected to the foot of the column A, and the negative

pole to the top of B. The current passes up A and thence by a copper wire to the binding screw, *a*; thence into the cup, *o*; traverses the entire movable circuit in the direction of the arrows, reaches the cup, C, whence by a copper strip it passes to the foot of the column B, rises in this, and returns to the battery. When the current passes, the circuit moves away from the columns, and, after a few oscillations, comes to rest crosswise to its original position, thus showing that the ascending current in the columns and the descending current in the movable wire repel each other, thereby proving the first law.

The second law may be established by means of the same apparatus, replacing the movable circuit depicted in fig. 573 by another so arranged that the current ascends in both the columns and in the two branches of the circuit. When the movable circuit is displaced, and the current is passed, the latter returns briskly towards the columns.

Angular currents.—In the case of two angular currents, one fixed and the other movable, Ampère found that there was attraction when both the currents moved towards, or both away from, the apex of the angle; and that repulsion took place when, one current moving towards the apex, the other moved away from it. In other words, two straight currents tend to become parallel to each other with the currents flowing in the same direction.

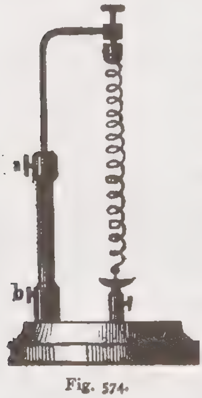


Fig. 574.

529. **Roget's vibrating spiral.** — The attraction between currents in the same direction may be very beautifully illustrated by *Roget's vibrating spiral* (fig. 574). A spiral of copper wire is fixed at one end to a binding screw, attached to an adjustable metal support, *a*; which, together with a binding screw, terminating in a cup, are fixed on a non-conducting base. The lower end of the spiral, which is weighted, dips in mercury in the cup. The poles of a battery being connected with the binding screws, the spiral at once begins to oscillate up and down. For the individual turns of the spiral are traversed by the current and attract each other; the spiral becomes shorter, its lower end no longer dips in the mercury, and the current ceases to pass. Owing to their weight, the windings,

being no longer attracted, sink again, the end dips in mercury, the current again passes, the individual turns again attract each other, and so on. The action is improved if a soft iron rod or a bundle of thin iron wires is introduced into the spiral.

SOLENOIDS

530. **Structure of a solenoid.**—A solenoid is a system of equal and parallel circular currents formed of the same piece of covered copper wire, and coiled in the form of a helix or spiral, as represented in fig. 575. A solenoid, however, is only complete when part of the wire passes in the direction of the axis in the interior of the helix, as shown in fig. 575. With this arrangement the solenoid, when supported by means of the pivots in two suitably placed mercury cups (see fig. 582), and a current passed through it, is directed by the earth exactly as if it were a magnetic needle. If the solenoid is deflected it will, after a few oscillations, rest with its axis in the magnetic meridian. Further, it will be found that, to an observer facing the north end of the solenoid, the current is circulating in the direction opposite to that in which the hands of a watch move. If he faces the south end, the direction of the current is the same as that of the hands of a watch.

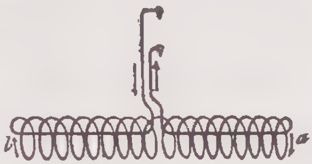


Fig. 575.

531. **De la Rive's floater.**—The properties of solenoids may be very conveniently illustrated and studied by means of what is known as *De la Rive's floater.* This consists of a copper wire bent in a ring or twisted in the form of a solenoid, the ends of the wire being soldered respectively to small plates of zinc and copper which are passed through a cork (fig. 576). If this apparatus is floated on a basin of slightly acidulated water, the voltaic action set up between the plates produces a current which traverses the solenoid. This then sets in a direction of magnetic north and south, and behaves in this respect just as if it were a magnet floated on a piece of cork (fig. 432).

If, instead of the solenoid in fig. 576, the wire is coiled in the form of a ring, and the pole of a magnetised bar is presented to the ring, it will be seen to move along the rod, which it encircles,

towards the middle, where it remains stationary. This action is illustrative of the general principle that when a coil or circuit in a

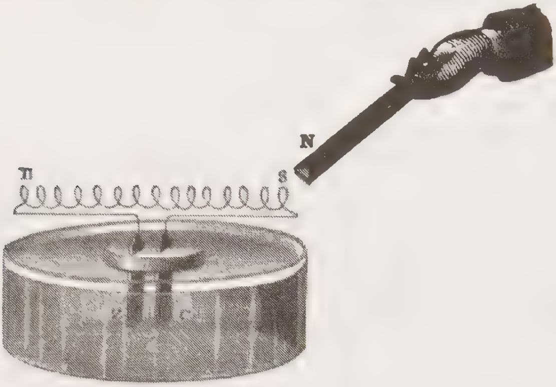


Fig. 576.

magnetic field is traversed by a current, it places itself so as to enclose the greatest number of lines of force.

532. **Mutual action of magnets and solenoids.**—The same phenomena of attraction and repulsion can be shown between two solenoids or between a solenoid and a magnet as between two

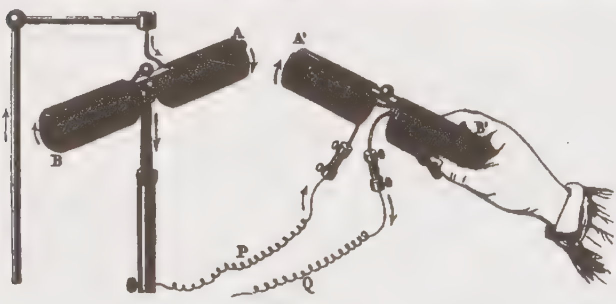


Fig. 577.

magnets. For if one of the poles of a magnet is presented to a movable solenoid, traversed by a current, attraction or repulsion will take place, according as the poles of the magnet and of the solenoid are of contrary or of the same name (fig. 577). The same

phenomenon takes place when a solenoid, traversed by a current and held in the hand, is presented to a movable magnetic needle. Hence the law of attractions and repulsions applies to the case of the mutual action of solenoids and of magnets. Similarly, when two solenoids traversed by a powerful current are allowed to act on each other, one of them being held in the hand, and the other being movable about a vertical axis as shown in fig. 577, attraction and repulsion will take place just as in the case of two magnets.

If a magnet is suspended just within the axis of a solenoid or magnetising spiral and a current is passed through it, then, according as the pole of the magnet and the spiral are opposite or are the same, the magnet is drawn into or repelled from the spiral. If, instead of a magnet, a soft iron rod is presented, this is drawn within the coil, and the more so the stronger the current. This principle is of frequent application in the regulation of arc lamps; and fig. 578 represents in section a *spring ammeter* based on it for measuring the strengths of currents, which from its simplicity may serve as an illustration of the technical instruments used for this purpose (527). S is a magnetising spiral terminating in binding screws. E is a thin cylinder of pure soft iron with an index *i*, and is attached to a spiral spring, *f*. The position of the spring can be adjusted by means of a screw, so that when no current passes the index is at zero of a scale at the side of the cylinder. By passing various currents of known strengths and noting the corresponding positions of the index, the scale is graduated, so that, on passing any current through, its strength in amperes is at once shown. The construction is improved by fixing a soft iron rod in the magnetising coil which projects inside the soft iron cylinder, E; this is magnetised by the current, and, adding its effect to that of the current, a greater degree of sensitiveness is obtained.

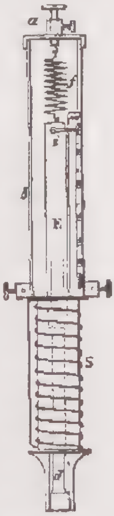


Fig. 578.

These phenomena are readily explained by reference to what has been said about the mutual actions of the currents, bearing in mind the direction of the currents in the ends A and A′ presented to each other.

533. **Ampère's theory of magnetism.**—Ampère propounded a most ingenious theory, based on the analogy which exists between

solenoids and magnets, by which all magnetic phenomena may be referred to electrodynamic principles.

Instead of attributing magnetic phenomena to the existence of two fluids, Ampère assumed that each individual molecule of a magnetic substance is traversed by an electric current. When the magnetic substance is not magnetised, these molecular currents, under the influence of their mutual attractions, occupy such positions that their total action on any external substance vanishes. Magnetisation consists in giving to these molecular currents a parallel direction, and the stronger the magnetising force the more perfect the parallelism. The *limit of magnetisation* is attained when the currents are completely parallel.

The resultant of the actions of all the molecular currents is equivalent to that of a single current which traverses the outside of a magnet. For by inspection of fig. 579, in which the molecular currents are represented by a series of small internal circles in the two ends of a cylindrical bar, it will be seen that the adjacent parts of the currents oppose one another, and cannot exercise any external electrodynamic action, which is not the case with those on the surface.

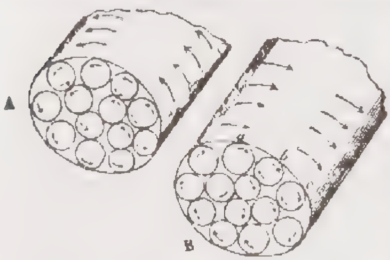


Fig. 579.

The direction of these currents in magnets can be ascertained by considering the suspended solenoid (fig. 575). If we suppose it traversed by a current, and in equilibrium in the magnetic meridian, it will set in such a position that in the lower half of each coil the current flows from *east* to *west*. We may then establish the following rule :—

To an observer facing the north pole of a magnet the direction of the Ampèrean currents is opposite that of the motion of the hands of a watch, and at the south pole the direction is the same as that of the hands.

534. **Terrestrial current.**—In order to explain terrestrial magnetic effects on this supposition, the existence of electric currents is assumed which continually circulate round our globe from east to west, perpendicular to the magnetic meridian.

The resultant of their action is a single current traversing the magnetic equator from east to west. These currents are supposed to be thermoelectric currents (562) due to the variations of temperature caused by the successive influence of the sun on the different parts of the globe from east to west.

These currents direct magnetic needles; for a suspended magnetic needle comes to rest when the molecular currents on its under surface are parallel to, and in the same direction as, the earth currents. As the molecular currents are at right angles to the direction of its length, the needle places its greatest length at right angles to east and west—that is, it sets north and south. Natural magnetisation is, in accordance with this view, probably imparted in the same way to iron minerals.

535. **Vibrating wire. Barlow's wheel.**—An interesting example of the action of a magnet on an electric current is seen in the experiment represented in fig. 580. HQ is a wire playing in a loop connected with one pole of a battery, the other pole of which leads to a groove containing mercury which is between the poles of a horseshoe magnet. When the current passes, the wire vibrates either towards the magnet or away from it, according to the direction in which the current passes. This is readily understood if we consider the direction of the imaginary currents circulating in the magnets on Ampère's hypothesis. The molecular currents *ab* and *cd* on the side next the wire determine the motion; they attract a current going in the same direction, HQ, and the wire is moved inwards. Its contact with the mercury is soon broken; the current then ceases to pass; it falls again by its own weight, the current is again made, and so on, the end of the wire vibrating continually in and out of the mercury. If the current is in the opposite direction, that is from Q to H, there is repulsion between the molecular current in the magnets and in the wire; the molecular currents repel this, and the vibration is towards the outside. The result may of course be otherwise explained without reference to Ampère's theory. It has been seen (520) that a current in a straight wire produces a magnetic field all round it, and that if the wire be fixed a movable north pole in its neighbourhood tends to travel towards

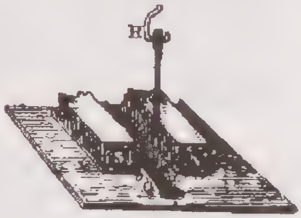


Fig. 580.

the left of an imaginary observer swimming with the current. Similarly, if the pole be fixed and the wire carrying the current be movable, the wire will move towards the right hand of the swimmer. This consideration leads at once to the result observed with the apparatus in fig. 580.

A further illustration is afforded by *Barlow's wheel* (fig. 581). This consists of a light copper disc, with deep indentations, forming a sort of star rotating easily in a fork, and the points just dipping in a groove containing mercury between the poles of a horseshoe magnet. When wires from a battery are connected as shown in the figure, the star at once rotates, and the direction of the rotation depends on the direction of the current.

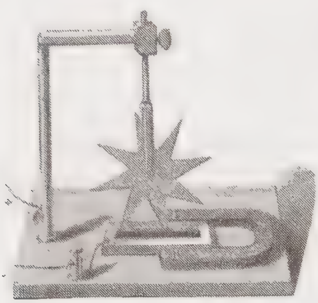


Fig. 581.

If, as shown in the figure, the current passes downwards through a vertical spoke, the latter moves towards the right, contact is then broken and made by another spoke, and the spokes follow in such rapid succession as to produce continuous rotation.

This result may be explained on Ampère's theory, or, more easily, by reference to the imaginary swimmer.

536. **Action of magnets and of the earth on currents.**—A further illustration of the mutual action of currents and magnets is afforded by the apparatus illustrated in fig. 582. A circle of copper wire, provided at the end with steel points, dips in two mercury cups. These mercury cups are at the ends of two metal rods attached to two vertical columns, with which can be connected a cell or battery. By this arrangement, which is known as *Ampère's stand*, we have a movable circuit traversed by a current. When the hoop is at rest, if a powerful magnet be placed beneath it, but in its plane, the circuit will be seen to turn and *set transversely to the length of the bar, which is the converse of Oersted's experiment.*

The terrestrial globe, which acts like a magnet on magnetic needles, acts in the same manner on the movable circuits—that is, it causes them to set at right angles to the magnetic meridian. This action may be demonstrated by the above apparatus. Let the hoop, before the circuit is completed, be placed in the magnetic

meridian, and then the two poles of the battery connected with the two columns ; the circuit is soon observed to set transversely to its first position, and in such a way that, in the lower part of the circuit, the direction of the current is from east to west.

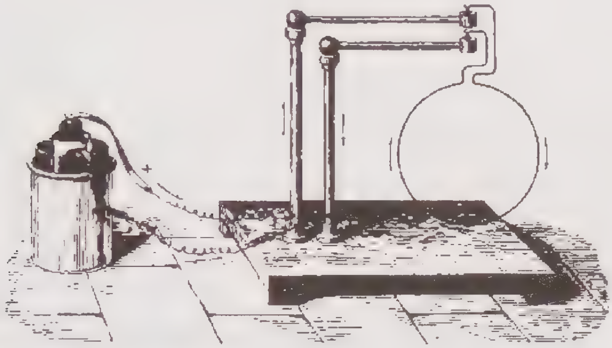


Fig. 582.

The hoop with its circulating current behaves, when placed in a magnetic field, exactly like a thin disc of steel magnetised with one face north and the other south. Such a disc, if suspended by a point on its circumference, will settle to rest with its north pole towards the magnetic north, and its plane perpendicular to the magnetic meridian.

CHAPTER XI

ELECTROMAGNETS. TELEGRAPHS

537. **Electromagnets.**—When an insulated copper wire is coiled round a rod of magnetic substance (fig. 583), and a current passed through the wire, the rod becomes magnetised, the more strongly the greater the number of turns of wire coiled on it, and the stronger the current. In other words, the magnetic effect is proportional to the number of *ampere-turns*. One end of the rod is a north pole, the other end a south pole. The lines of force due

Fig. 583.

to the magnetised rod may be investigated by means of iron filings (411), and will be found to be exactly similar to those observed with an ordinary steel magnet. If the rod experimented on is of steel, a large part of the magnetism remains after the circuit has been broken. The steel is permanently magnetised, and indeed this is the most effective method of making a permanent magnet. If the rod is of soft wrought iron, the magnetism acquired is

Fig. 584.

greater than in the case of steel, but lasts only so long as the current flows. Practically all the magnetism disappears when the circuit is broken. If the current is reversed, the polarity is simultaneously reversed. The connection between the direction of winding, the direction of the current, and the polarity of the magnet is shown in figs. 583 and 584. In the former the winding is right-handed, in the latter left-handed, but in both it will be noticed that if to an observer looking at the end of the coil the current is going round in the same direction as the hands of a

watch, that end of the rod is a south pole. Or the rule may be stated thus: the north pole will always be to the left of a swimmer in the wire, who is swimming with the current and looking towards the magnetised core.

Electromagnets are bars of soft iron which, under the influence of a voltaic current, become magnets; they frequently have the horseshoe form, as shown in fig. 585, and several layers of insulated copper wire are wrapped round them on the two branches, so as to form two bobbins, A and B. In order that the two ends of the horseshoe may be of opposite polarity, the winding on the two limbs, A and B, must be such that if the horseshoe were straightened out it would be in the same direction.

The core of an electromagnet, instead of being made in one piece, is more usually constructed of two iron cylinders, firmly screwed to a stout piece of the same metal, called the *yoke*. Such are the electromagnets in Morse's telegraph (fig. 587).

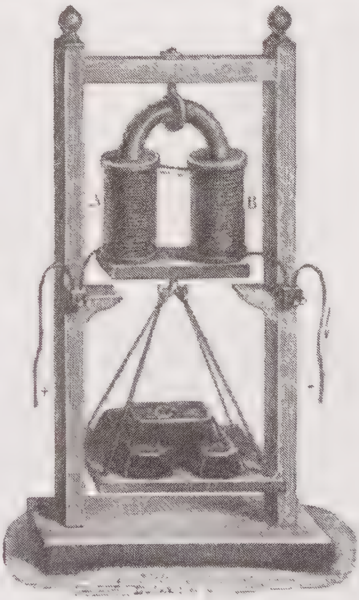


Fig. 585.

The lifting power or traction of an electromagnet (fig. 585) depends upon the number of ampere-turns, the diameter of iron core, and the closeness of contact between the poles and the keeper. An electromagnet need not be very powerful to support one person (fig. 585).

538. **Electric telegraphs.** These are apparatus by which signals can be transmitted to considerable distances, and with enormous speed, by means of electric currents propagated in metal wires. Towards the end of the last century, and at the beginning of the present, many philosophers proposed to correspond at a distance by means of the effects produced by electric machines when propagated in insulated

conducting wires. In 1811 Soemmering invented a telegraph in which he used the decomposition of water for giving signals. In 1820, at a time when the electromagnet was unknown, Ampère proposed to correspond by means of magnetic needles, above which a current was sent, as many wires and needles being used as letters were required. In 1834 Gauss and Weber constructed an electromagnetic telegraph, in which a voltaic current transmitted by a wire acted on a magnetised bar, the oscillations of which, under its influence, were observed by a telescope. They succeeded thus in sending signals from the Observatory to the Physical Cabinet in Göttingen, a distance of a mile and a quarter, and to them belongs the honour of having first demonstrated experimentally the possibility of electric communication at a considerable distance. In 1837 Steinheil in Munich, and Wheatstone in London, constructed

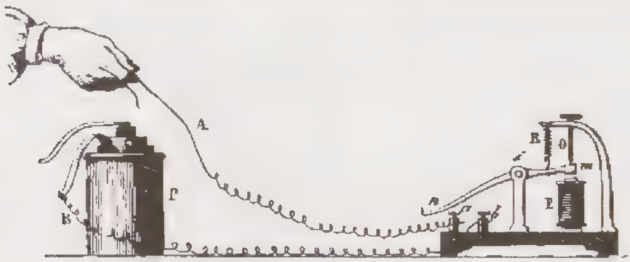


Fig. 586.

telegraphs in which several wires each acted on a single needle, the current being produced in the first case by an electromagnetic machine, and in the second by a constant battery.

Every electric telegraph consists essentially of three parts: 1, a *circuit*, consisting of a metallic connection between two places, and a source of electric current; 2, a *communicator* or *sender*, for sending the signals from one of the stations; and, 3, an *indicator* or *receiver*, for receiving them at the other station. The manner in which these objects, especially the last two, are effected can be greatly varied. The three principal systems are the needle telegraph, the dial telegraph, and the Morse telegraph.

The *needle telegraph* is essentially a vertical galvanometer (521); that is to say, a magnetic needle suspended vertically in a coil of insulated wire. To the needle is attached an index, which is seen

on the front of the apparatus. The signs are made by transmitting the current in different directions through the galvanometer, by which the needle is deflected either to the right or left, according to the will of the operator. The instrument by which this is effected is called a *key*, or *commutator*.

In the *dial* telegraph an electromagnet causes an index to move over a dial provided with the twenty-six letters of the alphabet, that letter in front of which the needle stops being the letter sent. By this kind of telegraph messages are not sent with great rapidity, and the mechanism is somewhat complicated and apt to get out of order; yet, as the manipulation is very simple, it is occasionally found in private offices.

539. **Principle of Morse's telegraph.**—This telegraph is based *on the temporary magnetisation of soft iron by the intermittent*

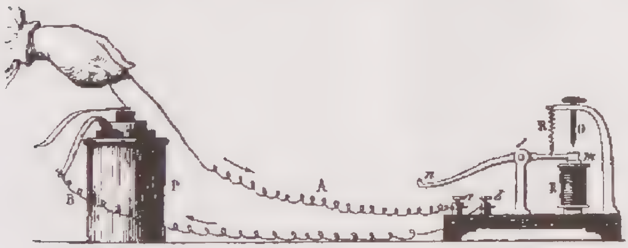


Fig. 587.

passage of currents. Thus let E (fig. 586) be a fixed electromagnet, the insulated wires of which are attached to the two binding screws, *a* and *b*. Above this electromagnet is a lever, *mn*, movable about an axis, *i*, and ending in an armature of soft iron, *m*, so that, whenever the electromagnet is traversed by a current, the armature is attracted, and the part of the lever on the right of the fulcrum is lowered; then, when the current no longer passes, a spring, R, raises the lever to an extent regulated by a screw, O.

Suppose, for example, the electromagnet is at Bristol, and that there is a cell, P, at London, and two metal wires, A and B, by one of which the binding screw, *b*, is permanently connected with the negative pole of the battery, while the experimenter holds the other wire in his hand. So long as the experimenter does not place the wire, which he holds in his hand, in contact with the positive

pole, the current does not pass ; and as the electromagnet does not act, the arm, *im*, of the lever is raised (fig. 586). But the moment contact is made the circuit is closed, the electromagnet attracts, and the arm, *im*, is lowered (fig. 587) ; but it resumes its original position as soon as contact is broken, and so on at the will of the operator. Thus one person at London can cause the lever, *mn*, to oscillate at Bristol as often and as rapidly as he desires. This is, in its simplest form, the principle of the elementary mechanism of electric telegraphs based on electromagnetism. It only remains to give to these oscillations a definite meaning (543).

540. **Line wire.**—Of the various essentials for telegraphic communication, the batteries or sources of power have been already described, and we shall therefore pass to the explanation of the *circuit*, or *line wire*.

Fig. 588.

Line wires are either *air*, *subterranean*, or *submarine*.

The air wire consists of a stout galvanised iron wire connecting two stations. At certain intervals are wooden posts, to which are attached insulating supports of porcelain, which sustain the wire (fig. 588). Subterranean wires are used in cases in which an aërial wire would not be sufficiently protected against accident, as in towns. They usually consist of copper wires covered with gutta-percha ; this insulates them from the earth in which they are placed.

Submarine wires or cables are such as are employed in deep seas, where great strength is required. The ordinary form is represented in figs. 589 and 590. The *core* consists of seven fine wires of very pure copper, which are twisted together. This is surrounded by an insulating coating of four consecutive layers of gutta-percha, alternating with the same number of layers of a material known as *Chatterton's compound*, which is essentially a mixture of resin, pitch, and gutta-percha applied hot. Round this is a layer of tarred hemp, and this again is surrounded by a protective coating of steel wire coated with tarred hemp, which preserves it from the corrosive action of the sea.

Fig. 589 gives a longitudinal view of a submarine cable, and fig. 590 a cross section. The diameter of such a cable is about an

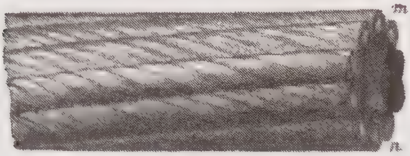


Fig. 589.

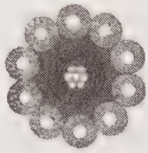


Fig. 590.

inch, it weighs about a ton to the mile, and its resistance is from $3\frac{1}{2}$ to 10 ohms per mile.

541. **The earth as a conductor.**—In figs. 586 and 587 we have not merely a wire connecting the positive pole of the battery with the electromagnet, but there is a second one which acts as a return wire. In 1837 Steinheil made the very important discovery that the earth might be utilised for the return conductor. This

Fig. 591.

has the twofold advantage of doing away with the expense of a second wire and also of lessening the resistance.

With this view, at the sending station, a copper wire is attached to the negative pole, which is fixed at the other end to a copper plate, Q. This plate is placed in water if possible (fig. 591), or at all events is sunk some depth in earth, the object being the same as in making the earth connection of a lightning-conductor. In like manner, at the receiving station, a similar wire and plate, S, are connected with the binding screw, *b*. Thus, the circuit is

completed by the earth between the plates Q and S, and the electricity circulates exactly in the same way as when, instead of the earth, there was a metallic return wire, B (fig. 586). The resistance between the plates Q and S is comparatively small, and, provided they are not too close together, is independent of their distance apart.

542. **Morse's telegraph.**—Fig. 592 represents a station at which a despatch is being sent by the help of this apparatus, and fig.

Fig. 592.

593 represents the receiving station. At each station the apparatus is the same; it is double, and consists of two distinct parts—the *key*, by which the signals are sent, and the *receiving instrument*, which registers them. The two parts are represented on a larger scale in figs. 594 and 595.

To understand how they work, let us begin with fig 592. Below the table is a box containing the battery, which furnishes the current. The current passes by the wire, P, into the key, which will be afterwards described (fig. 594). Thence it passes into a small galvanometer, *g*, which indicates by the deflection of its needle whether the current is passing or not. The current ultimately attains the

Fig. 593.

piece, M, which acts as a lightning-conductor, as we shall afterwards see, and thence it goes to the wire, L, which is the *line wire*.

This wire is again seen at the top of fig. 593, whence the arriving current again passes into the lightning-conductor, then into a galvanometer, and next to a key, whence it passes into the electromagnet, which makes part of the receiver. It then enters the wire, T, which leads it to earth.

§ 543. **Morse's key and receiving instrument.**—The general arrangement of the apparatus being understood, the following are the details of its action. The *key* consists of a small mahogany base, which acts as a support for a metal lever, *hk* (fig. 594), movable about a horizontal axis in the middle. The end, B, of this lever is always pressed upwards by a spring, *r*, beneath; at the other end a screw passes through it, which rests on a small metal support in contact with the wire, A. Fig. 594 represents the key at the moment it receives the despatch, as at work, for instance, in fig. 595. The current enters then by the wire, L, which is the line wire, rises into the lever, *hk*, and descends by the screw pin, *a*, into the wire, A, which leads to the indicator. If, on the other hand, the key is to be used for sending a message, as represented in fig. 592, it will be seen that the lever, *kh*, does not touch the metal pin in which the wire, P, terminates. But if the lever, *h*, is lowered by pressing the end, B, the current, P, at once passes into the lever, *hk*, and thence into the wire, L, which leads it to the station signalled to; for the same wire is used to send and to receive the message.

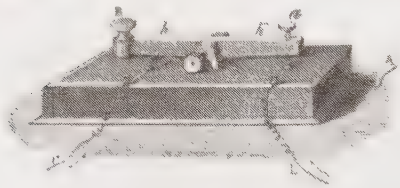


Fig. 594.

The *indicator* or receiver consists of an electromagnet, E (fig. 595), which, whenever the current is transmitted, attracts an armature of soft iron, *m*, fixed at the end of a lever, *mn*, movable about an axis; when the circuit is open, the lever is raised by a spring, R. At the other end of the lever there is a pencil, *x*, which writes the signals. For this purpose a long band of strong paper, *ab*, rolled round a drum S (figs. 592 and 593), passes between two brass rollers with a rough surface, turn-

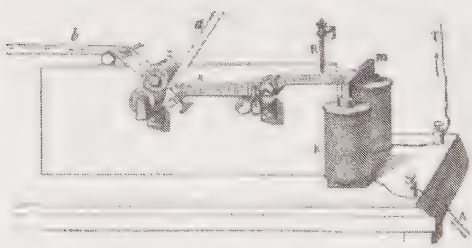


Fig. 595.

ing in contrary directions. Drawn in the direction of the arrows, the band of paper becomes rolled on a second drum, which is turned by hand. A clockwork motion placed in a box, V, works the rollers between which the band of paper passes.

The paper being thus set in motion, whenever the electromagnet works, the point, x, strikes the paper, and, without perforating it, produces an indentation, the shape of which depends on the time during which the point is in contact with the paper. If it only strikes it instantaneously, it makes a dot (·); but if the contact is of any greater duration, a line or dash (—) of corresponding length is produced. Hence, by varying the length of contact of the transmitting key at one station, a combination of dots or dashes may be produced at another station, and it is only necessary to give a definite meaning to these combinations.

This is effected as follows in Morse's alphabet :—

	Printing.	Single Needle.		Printing.	Single Needle.
A	· —	\/	N	— ·	/\
B	— · · ·	/\\\	O	— — —	///
C	— · — ·	/\/\	P	· — — ·	\//\
D	— · ·	/\\	Q	— — · —	//\/
E	·	\	R	· — ·	\/\
F	· · — ·	\\/\	S	· · ·	\\\
G	— — ·	//\	T	—	/
H	· · · ·	\\\\	U	· · —	\\/
I	· ·	\\	V	· · · —	\\\/
J	· — — —	\///	W	· — —	\//
K	— · —	/\/	X	— · · —	/\\/
L	· — · ·	\/\\	Y	— · — —	/\//
M	— —	//	Z	— — · ·	//\\

Fig. 596.

The other signals are those of the single-needle instrument (538). The signal \ denotes a deflection of the top of the vertical

needle to the left, and the signal / to the right. They correspond respectively to the dot and dash of the Morse alphabet.

544. **The sounder.**—Any one present while a message is being received at a telegraph station is astonished at the promptitude and accuracy with which signals are read and transmitted by the operators. These acquire such skill that they can read a message by the sounds which the armature makes in striking against the electromagnet of the indicator.

Based on this fact, a form of instrument invented in America has come into use for the purpose of reading by sound. The *sounder*, as it is called, is essentially a small electromagnet on an ebonite base, resembling the relay in fig. 599. The armature is attached to one end of a lever, and is kept at a certain distance from the electromagnet by a spring. When the current passes, the armature is attracted against the electromagnet with a sharp click, and when the current ceases it is withdrawn by the spring. Hence the interval between the sounds is of longer or shorter duration according to the will of the sender, and thus in effect a series of short and long sounds can be produced, which correspond respectively to the dots and dashes of the Morse alphabet.

545. **Improvements in Morse's telegraph.**—In the apparatus just described, the indentations on the paper only give indistinct

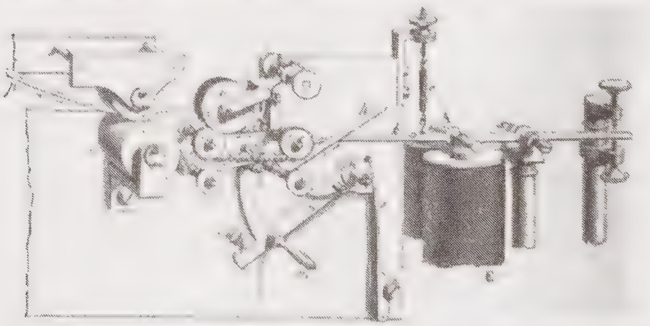


Fig. 597.

dots and dashes, unless the current transmitted be very powerful. To get rid of this inconvenience, and to expend less force, the apparatus has been modified so that the signals can be traced in ink. With this view, all the other parts being the same, the following arrangement is made :—

A roller, *a*, fig. 597, covered with flannel, is moistened with a suitable ink, and is in contact with an endless band passing round on two pulleys, *o*, *o′*, which are turned by the clockwork motion which moves the paper. The paper is kept by a roller, *b*, very near the inked band, but not touching it. That being premised, whenever the current passes in the electromagnet, the armature, A, is attracted, the arm of the lever, *k*, is depressed, and a pin, *i*, at its end rests on the band, and places it in contact with the paper. The band, depositing the ink which it has taken from the roller, makes on the paper, as it moves along, a dot or a dash according to the length of time the current passes, which dots and dashes have the same meaning as above.

546. **Lightning-conductor.**—Besides the parts of the telegraph already described, there are three of which mention must be made: the *lightning-conductor*, the *bell* or *alarum*, and the *relay*.

The object of the lightning-conductor is to preserve the telegraphic instruments from damage due to lightning discharges which may have struck some part of the circuit with which the instruments are in connection. It is well known that a sudden charge of electricity like that of a lightning flash, in making its way to earth, will more readily jump across an air space than pass through a coil of wire. The lightning-conductor is so constructed as to utilise this principle and divert the discharge from the instruments.

Represented at M in figs. 592 and 593, it consists of a vertical stand on which are two copper plates, indented like a saw, and arranged so that the teeth are near each other but do not touch. One of these plates is connected with the earth, the other with the line wire. Hence, when, from any cause, a discharge of electricity reaches the apparatus, it escapes by the points to the plate which is connected with the ground, and thus all danger to the instruments is avoided.

547. **Electric bell.**—The electric bell is intended to warn the receiving station that a message is about to be sent. Represented in fig. 598, it consists of a board on which is fixed an electromagnet by means of a piece of brass, E. The current from the line arriving by a binding screw, *m*, passes to the wire of the electromagnet, thence into the armature, *a*, into a steel spring, *c*, which presses against the armature, and ultimately emerges by a second terminal, *n*.

Thus, whenever the current of the line wire reaches the electromagnet, the armature, *a*, is attracted, and a clapper, P, fixed to this

armature, strikes against a bell, T, and makes it sound. The moment the clapper strikes, as the armature is no longer in contact with the spring, C, the circuit is broken, the electromagnet no longer attracts, and the armature reverts to its original position by the action of a spring, *e*, to which it is fixed.

The circuit being closed afresh, a second attraction takes place, and so on until the telegraph clerk, thus warned, lets the current pass directly into the receiver without passing through the bell. This he accomplishes by connecting the terminals *m* and *n* by a short strip of brass by means of an arrangement called a *shunt* (526).

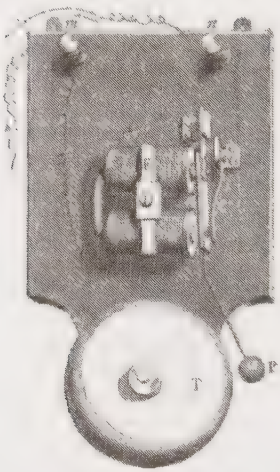


Fig. 598.

Relay.—In describing the receiver, we have assumed that the current of the line coming by the long wire, A (fig. 587), entered directly into the electromagnet, and worked the armature, E ; but when the current has to traverse a distance of a few miles, owing to the resistance of the wire and the losses due to bad insulation, its strength is so greatly diminished that it cannot act upon the electromagnet with sufficient force to print a despatch. Hence it is necessary to have recourse to a relay ; that is, to an auxiliary electromagnet, which is still traversed by the current of the line, but which serves to introduce into the circuit of the Morse instrument the current of a sufficiently powerful *local battery* placed at the station, and only used to print the signals transmitted by the wire.

For this purpose the current from the line entering the relay by the binding screw, L (fig. 599), passes into an electromagnet, E, whence it passes into the earth by the binding screw, T. Now, each time that the current of the line passes into the relay the electromagnet attracts an armature, A, fixed at the bottom of a vertical lever, *p*, which oscillates about a horizontal axis.

At each oscillation the top of the lever, *p*, strikes against a button, *n*, and at this moment the current of the local battery,

which enters by the binding screw, *c*, ascends the column, *m*, passes into the lever, *p*, and, by an insulated contact not shown in the figure, descends by the rod, *o*, which transmits it to the binding screw, Z; thence it enters the electromagnet of the indicator, whence it emerges to return to the local battery from which it started, and thus completes the circuit. Thus, when the current in

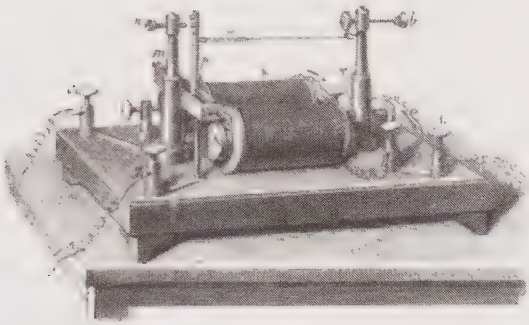


Fig. 599.

the line ceases, the electromagnet of the relay, E, does not act, and the lever, *p*, drawn by a spring, *r*, leaves the button, *n*, as shown in the drawing, and the local current no longer passes. Thus the relay transmits to the indicator exactly the same phases of make and break, dot and dash, as those produced by the key in the station which sends the despatch.

CHAPTER XII

CURRENT INDUCTION

548. **Induction by currents.**—We have already seen (444) that by the term *induction* is meant the action which electrified bodies exert at a distance on bodies in the natural state. Hitherto we have only had to deal with electrostatic induction; we shall now see that dynamic electricity produces analogous effects.

Faraday discovered this class of phenomena in 1832, and he gave the name of *currents of induction* or *induced currents* to instantaneous currents developed in metallic conductors by the

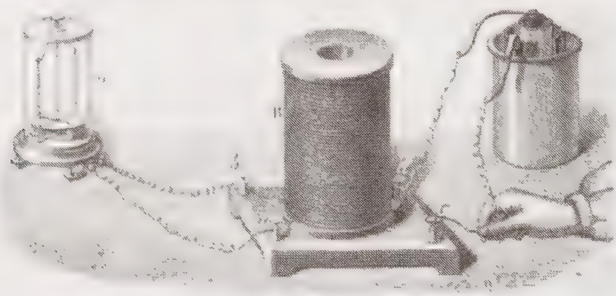


Fig. 600.

influence or induction of metallic conductors traversed by electric currents, or by the influence of powerful magnets, or even by the magnetic action of the earth; and the currents which give rise to them he called *inducing currents.*

The inductive action of currents at the moment of opening or closing may be shown by means of a coil with two wires. This consists (fig. 600) of a hollow cylinder of wood or of cardboard, on which a quantity of stout silk-covered copper wire is coiled; on this is again coiled a considerably greater length of fine copper wire,

also insulated by being covered with silk. This latter coil, which is called the *secondary coil*, is connected by its ends with two binding screws, *a*, *b*, from which wires pass to a galvanometer, G, while the thicker wire, the *primary coil*, is connected by its extremities with two binding screws, *c* and *d*. One of these, *d*, being joined to one pole of a battery, when a wire from the other pole is connected with *c*, the current passes in the primary coil, and in this alone. The following phenomena are then observed :—

i. At the moment of completing the primary circuit the galvanometer, by the deflection of the needle, indicates the existence in the *secondary coil* of a current *inverse* to that in the primary coil,

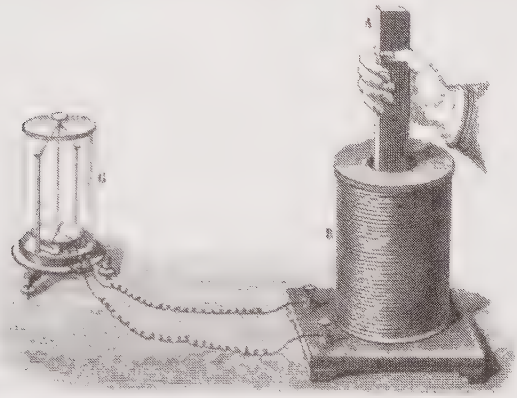


Fig. 601.

that is, in the contrary direction ; this is only momentary, for the needle immediately reverts to zero, and remains so as long as the inducing current passes continuously through *ca*.

ii. At the moment at which the primary current is stopped—that is, when the wire *cd* ceases to be traversed by a current—there is again produced in the wire *ab* an induced current, instantaneous like the first, but *direct* ; that is, in the same direction as the inducing current.

549. **Induction by magnets and by the action of the earth.**—It has been seen that the influence of a current magnetises a steel bar ; in like manner a magnet can produce induced electric currents in metallic circuits. Faraday first showed this by means

of a coil with a single wire of 200 to 300 yards in length. The two extremities of the wire being connected with the galvanometer, as shown in fig. 601, one end of a bar magnet is suddenly inserted in the bobbin, and the following phenomena are observed :—

i. At the moment at which the magnet, A, is introduced, the galvanometer indicates in the wire the existence of an *inverse* current ; one, that is to say, the direction of which is opposed to that which circulates round the magnet, considering the latter as a solenoid on Ampère's theory (533).

ii. The needle at once returns to zero, and remains there as long as the magnet is at rest in the coil ; when it is withdrawn, the needle of the galvanometer indicates the passage of a direct momentary current ; that is, one in the opposite direction to the first.

These effects are also produced if the experiment is made with a coil conveying a current instead of with the magnet represented in fig. 601.

The inductive action of magnets may also be illustrated by the following experiment :—A bar of soft iron, or, still better, a bundle of soft iron wires, is placed in the above coil, and one pole, N, of a strong magnet is suddenly brought in contact with it ; the needle of the galvanometer is deflected, but returns to zero when the magnet is stationary, and is deflected in the opposite direction when it is removed. If the experiment is repeated by inducing the opposite pole, S, the effects will be the same, though the direction of the current will be the exact opposite. The induction is here produced by the magnetisation of the soft iron bar in the interior of the bobbin under the influence of the magnet.

A current is induced in a coil forming part of a closed circuit if the lines of force passing through it are in any way altered. If the number of lines is increased the current will be in one direction, if diminished in the opposite. But so long as the number (whether large or small) remains constant, there will be no induced current. This general statement comprises all the cases mentioned above.

Faraday discovered that terrestrial magnetism can develop induced currents in metallic bodies in motion, and that it acts like a powerful magnet placed in the interior of the earth, or, according to the theory of Ampère, like a series of electric currents directed from east to west parallel to the magnetic equator. He first proved this by placing a flat coil of wire with its plane perpendicular to the dip needle. On rapidly turning this coil through a semicircle

about a diameter, he observed that at each turn the needle of a galvanometer, connected with the two ends of the coil, was deflected.

550. **Extra current.**—A long length of insulated wire is wound closely so as to form a compact spiral, and one of the free ends is connected with one pole of a battery of two or three cells, the other pole of which is connected with a mercury cup. On *making* the circuit, by placing the free end of the coil in the mercury, a scarcely perceptible spark is obtained. But on *breaking* the circuit, by taking the end out of the cup, the spark produced is much longer, brighter, and denser.

This is due to an inductive action which each of the windings of the coil exerts on its neighbours, producing a current opposite in direction to its own, the effect of which is to *retard* the establishment of the steady current.

When the circuit is broken, inductive action again takes place, but its direction is the same as that of the current ; its effect would be to prolong the current, but since the circuit is broken, the electromotive force of the induction adds itself to that of the disappearing current, and a far more powerful spark is produced. This may be compared in its effects to what takes place when we suddenly turn the cock of a high-pressure water service with the flow on ; the momentum will sometimes burst the pipe, and in like manner this sudden cessation of the current may destroy the insulation of the coil.

The phenomenon described is known as that of *self-induction*, and the current produced was called by Faraday, the discoverer, the *extra current*.

Its existence may be demonstrated by interposing the body as a shunt (526) in a circuit containing *a single* Grove or Bunsen cell and a large electromagnet. If the hands are wetted and one hand firmly grasps an old file connected with one terminal, while a wire from the second terminal is drawn along the teeth of the file by the other hand, brilliant sparks are seen, due to the successive making and breaking of the circuit, and violent shocks are felt in the hands and arms. The intensity of the effect depends on the *change* in the number of lines of force enclosed by the circuit at each break. Hence the necessity for a large electromagnet (*i.e.* large self-induction).

The effects of self-induction may be illustrated by the following experiment. An alternating current (551) divides into two

branches, one of which is a coil of insulated wire, while there is a glow-lamp in the other; the current is so adjusted that the lamp just glows (fig. 602). If now a soft iron bar is suddenly inserted in the coil, the lamp glows brightly for an instant; the effect is as if the resistance of the branch containing the coil had been momentarily increased, so that a larger portion of the current had been diverted through the lamp. This apparent increased resistance is due to an increase of the self-induction by the presence of the iron in the coil. The sudden increase in the number of lines passing through the coil gives rise to an opposing E.M.F., which diminishes the current in the coil, and causes the increased glow of the lamp.

Fig. 602.

551. **Magnetoelectric machines.**—If in the experiment described above (fig. 601) we had some arrangement by which the magnet, A, could be rapidly and regularly moved in and out of the coil, B, the ends of which were joined either directly or by the intervention of a galvanometer, we should have a series of alternating currents produced in the circuit. The result is the same if, while the magnet is fixed, the coil is moved towards it—a current will be produced in a particular direction; when the coil is moved away a momentary current is also produced, but in the opposite direction. Both in this case and in the experiments described above, the currents are only produced while the relative positions of the coil and the magnet are being altered; that is, while the number of lines of force passing through the coil is increasing or diminishing.

Magnetoelectric machines are apparatus which are based on these experiments. Fig. 603 represents the essential features of one of the simpler forms, such as is used for medical purposes, and is selected as conveniently illustrating the principle. NS is a horseshoe magnet firmly fixed in a suitable position—instead of a solid magnet a battery of several magnetic plates is often used—in front of the ends of which are two coils or bobbins of wire, CD, fitted on soft iron cores which are screwed to the soft iron plate,

or *yoke*, BB. By means of the handle fixed to the axis, AA, these coils can be rotated in front of the poles, NS. The ends of the wires, *mn*, are connected to an arrangement on which press two fork-shaped springs, insulated by a plate of ebonite from each other, and from the magnet to which they are screwed. With these are connected two wires which form the electrodes, to which are affixed handles, P and Q.

Let us first suppose the bobbins to be at rest in the position shown in the figure, C over N, and D over S. The lines of force due to the horseshoe magnet pass from N through the air-gap up C, through the yoke B, down D, and across the air-gap to the south pole of the magnet. The iron cores and yoke act as a sort of keeper to the magnet, and the number of lines passing through the coils is large in consequence ; but there is no induced current while the coils are at rest. We suppose that P and Q are connected so that the circuit is complete. Now let the coils rotate uniformly, and consider the changes in the number and direction of the lines of force which pass through C and D during one complete revolution. As C moves upwards from the plane of the paper, the (upward) lines of force which pass through it *diminish* in number, and therefore there will be an induced current in the circuit, which we will call *positive*. The lines through C vanish when C has passed through a quarter of a revolution. As C moves through the second quadrant, the lines through it *increase*, and their direction is now *downwards* because C is nearer to S than to N. Hence the current is still *positive*. If we follow the motion of C through the third quadrant, we shall see that the current is reversed ; it is now *negative*. For, as C moves away from S, the lines of force in it *diminish* and are *downwards*. Lastly, during the revolution of the coils through the fourth quadrant, the number of lines through C is *increasing* and their direction is *upwards*, and therefore the

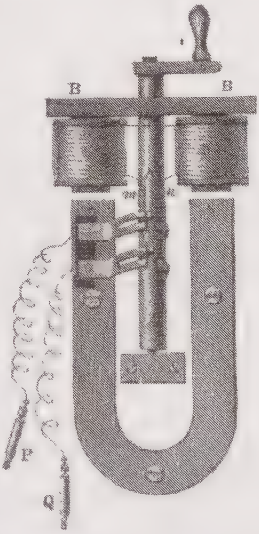


Fig. 603.

current has the same sign as when they were *diminishing* and *downwards*. The current is positive if the lines are diminishing downwards or increasing upwards ; it is negative if they are increasing downwards or diminishing upwards.

What is true of the one coil, C, is true of the other, D, also. Care is taken that the wire is coiled on the two bobbins in such a manner that the effect in each half-revolution is the same, and thus double the effect is produced.

Hence, during a complete revolution of the coils, two currents are produced exactly alike, but alternately opposite in direction. Such currents are called *alternate* or *alternating* currents. For some purposes, such as for physiological effects, heating and lighting effects, this is of no moment ; but where a continuous current is required, as in electroplating, it is necessary to adjust the currents so that they will all go in the same direction. This is effected in the above machine by means of the *commutator* represented on a large scale in fig. 604. On the axis, AA, are four semicircular *half*-rings of metal, insulated from each other and from the axis ; the wires, *m* and *n*, from the coils (fig. 603) are connected with these rings, *m* with *a* and *d*, and *n* with *b* and *c* Now we have seen that the currents in *m* and *n* are alternately positive and negative. When *m* is positive, *a* is positive and *c* is negative ; the contact springs, *x* and *y*, press on *a* and *c*, and the current travels from *x* to *y*, and so to the electrodes ; but when in the rotation of the coils, C and D, the current is reversed, and *m* is now negative and *n* positive, the spring *x* presses on *b* and *y* on *d*, so that the direction of the current is still from *x* to *y*.

Fig. 604.

552. **Gramme's magnetoelectric machine.**—An improved magnetoelectric machine is that invented by Gramme, which gives continuous currents. One form of this apparatus which is designed for lecture purposes is represented in fig. 605. It consists of a horseshoe magnetic battery, one, that is, consisting of a number of thin steel plates magnetised separately, and then joined together, and provided at the ends with soft iron pieces which form the poles. Between these is a ring-shaped armature or *inductor*, which is the characteristic feature of the apparatus ; its principle was first discovered by Pacinotti, and that depicted in fig. 605, which

is a modification of Pacinotti's, is known as *Gramme's ring*. It consists, not of a solid ring of soft iron, but of one made by coiling a great length of fine iron wire. Round this is wound at right angles a series of separate coils of insulated wire, which are represented alternately black and white. On the centre of the ring, and rotating with it, is a cylinder made up of alternate strips of metal and insulator, known as the commutator segments. The coils on the ring form a continuous whole, for the end of each one is joined to one of the metal strips, as is also the beginning of the next. On this cylinder press flat bundles of wire, which constitute the *brushes*. When the ring is rotated, one of the supports of the collecting brushes becomes charged with positive and the

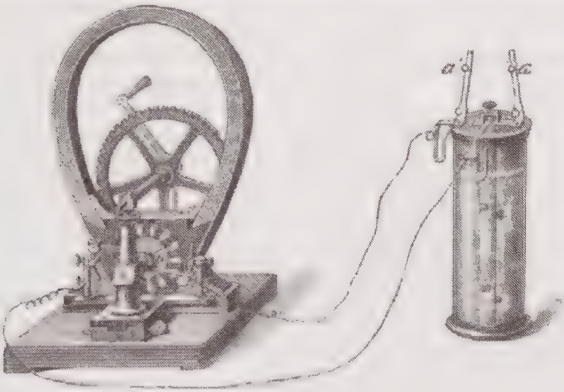


Fig. 605.

other with negative electricity ; they form the poles of the machine, so that when they are connected by a wire or by any apparatus—in the figure it is a secondary battery (516)—a current of electricity is produced which lasts as long as the rotation lasts. These currents are not alternating, like those of the machine described above (451) ; they are far more powerful, and are also direct—that is, they are always in the same direction. Space cannot here be given for an adequate explanation why the currents are direct ; it is sufficient to say that the various explanations given depend on a consideration of the direction of the induced currents developed by the poles of the permanent magnet in the coils of the armature its successive positions while rotating between them.

The currents produced by machines of this class, like that of any voltaic battery, depend in each case on the ratio of the electromotive force to the resistance of the circuit (507). The latter depends once for all on the length and diameter of the wire coiled on the ring inductor and on the external resistance; the electromotive force depends on the strength of the permanent field-magnets, and on the velocity with which the ring is rotated. Such an apparatus as that represented in fig. 605, when worked rapidly by hand, has an E.M.F. of about 15 volts.

Great improvements have of late years been made in the construction of magnetoelectric machines; partly by increasing the power and number in the magnets used to produce the field, partly by increasing the length and number of the coils and modifying the way in which the wire is coiled, and partly again by arranging them so that they come more completely within the action of the magnetic field. Such machines may be worked by water or by steam power, and they furnish the most practical and economical method of producing powerful electric currents. In principle this mode of producing electricity is cheaper than that of voltaic currents; but the electricity produced by magneto machines, if not worked by water power, and that of voltaic currents, both depend in the last resort upon the combustion of coal. In magnetoelectric machines the coal is directly consumed in working the steam engine which drives the machine; in the battery coal is used in the metallurgical extraction of zinc. Now it can be shown that the consumption of a given weight of coal can produce far more electricity in the former case than in the latter.

553. **Dynamoelectric machines.**—We may imagine in Gramme's machine that we have electromagnets excited by a voltaic battery instead of permanent steel magnets; it will be obvious that, since electromagnets are much more powerful than permanent magnets of the same size, the induction currents produced will be more powerful also. Machines in which this principle was applied were devised by Wilde, and far more powerful effects were produced by them than had hitherto been obtained.

A still more important improvement is the following—the principle of which was discovered by Sir C. Wheatstone, and by Sir W. Siemens independently, but first applied by the latter. Suppose that, instead of the permanent magnets, we have a horseshoe-shaped core of soft iron wrapped round with wire—that is, an electromagnet; and suppose further that the wires of this electro-

magnet are connected with those of the armature which rotates between its poles. There is always, even in the best soft iron, a trace of residual magnetism (425) which is sufficient to excite a weak induced electromotive force in the armature as it rotates; this E.M.F., if the circuit is complete, gives rise to a current which traverses the coils of the electromagnet, and increases the magnetisation of the core; this augmented magnetism in turn increases the strength of the currents in the inductor, and so this reciprocal action between the inductor and the electromagnet goes on producing an ever-increasing strength of current, which, indeed, in any particular case is only limited by the saturation of the iron and the speed of the inductor. Machines based on this principle, which transform mechanical energy into the energy of electric currents, are called *dynamoelectric*, or, more briefly, *dynamo machines*, in contradistinction to *magnetoelectric* machines, in which permanent magnets are used. Both are, however, strictly speaking, dynamo machines, for the electricity is in both cases produced at the expense of mechanical work.

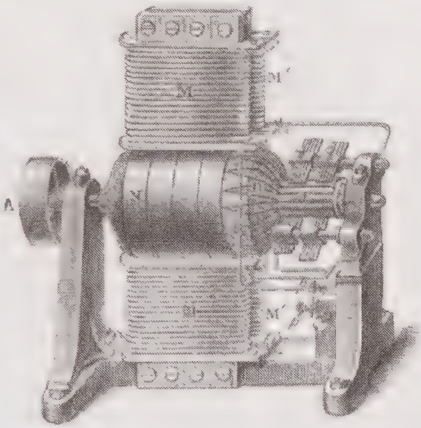


Fig. 606.

Fig. 606 represents the essential features of one of the small-sized vertical machines of this kind made by Messrs. Siemens. A characteristic is the *cylinder* or *drum armature*. The field magnets MM′ and MM′ have their similar poles joined together by the soft iron strips N (and S, not seen in the figure, on the further side of the machine), which are bent so as to almost completely encircle the armature; they are in detached pieces, so that air can freely circulate between them, and thereby the temperature be kept down.

The armature itself, D, consists of a number of discs of soft iron formed into a cylinder or drum and fixed to an axle which rests

in the strong upright supports, and is rotated by means of power transmitted to the pulley A. The wire is coiled on this ; one end is attached to a commutator segment as in Gramme's machine (552) ; it passes lengthwise round the drum in several turns, and the other end is attached to a similar segment, which is diametrically opposite the first. The wire is continuous, the connection of the individual strands being effected by means of the commutator segments. On these rest two pairs of brushes connected respectively with insulated binding screws, from which the current passes through the wires of the fixed magnets, and thence by the terminals, *pp*, to the external circuit.

The advantage of this construction is that from the length of the armature, and from the wires being on its surface and quite close to the poles of the fixed magnets, the influence of the latter is greater.

A small machine of this kind, which does not occupy a space of more than three cubic feet, and rotating with a velocity of 15 turns in a second, which is effected by 1½ horse-power, can produce an arc-light of 1,400 candles. The larger sizes produce far more powerful effects, but require, of course, greater power to work them. They are, however, relatively more economical.

554. **Electric transmission of power.**—If the binding screws of two Gramme's machines, or other dynamos, A and B (fig. 607), are connected by wires of even considerable length, and if one of them is rotated, the armature of the second one rotates with corresponding rapidity. Here the first machine furnishes the current at the expense of the work used in turning it, the second one is set in motion and transforms the energy of the current into mechanical energy. This application is of great importance, as it demonstrates the possibility of transmitting mechanical power to a distance by means of simple metal wires, and without the use of wheels, or shafting, or wire ropes, or water tubes, which are the usual modes of transmitting power. But electricity has the important advantage that, as has been proved by actual experiment, power can be transmitted by its means to considerable distances, while the transmission by the ordinary agencies is restricted to comparatively short distances.

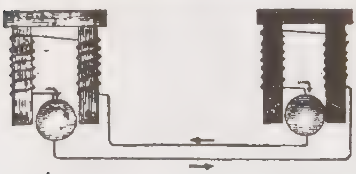


Fig. 607.

For the electric transmission of power three things are essential—a source of power, which on the large scale would be a gas or steam engine, or a water-wheel or turbine; a dynamo *generator*, and a second dynamo in conducting communication with the first, which is the *motor*; this can do the work which any other motor can do—turn machinery, saw wood, pump water, and the like. The whole of the energy of the mechanical motor—that which drives the generator—does not appear in the electromotor; some of it is transformed into heat in the conducting wires; but it has been found that as much as 70 per cent. of the energy of the motor can be transmitted even through over 100 miles of wire. This application has become of great service where natural sources of power are available, such as waterfalls and rivers, or possibly tidal energy. Water power is employed to work water-wheels or turbines, which in turn work some form of dynamo machine, and the electric power thus created is transmitted to the place where it is to be utilised, and thus new industrial centres may be created.

555. **Classification of dynamo machines.**—The principal types of dynamo machines are depicted in figs. 608-611, originally due to Professor Sylvanus Thompson. The armature rotates in the space between the large pole pieces of the field magnets in the clockwise direction. In the figures the commutator and brushes only are shown. Fig. 608 represents a machine the field magnets of which are excited by a separate machine or by a battery. It is known as a *separately excited* machine. The brushes are connected to the external circuit. The magnetic field in which the armature rotates will be constant if the exciting current is constant, and so the induced electromotive force which depends upon the rate of cutting the lines of force will be constant for a given speed of rotation. The action is in fact the same as that of the magneto-electric machine already described (552).

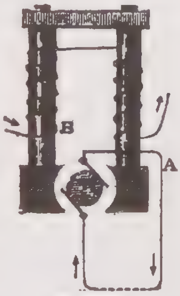


Fig. 608.

Fig. 609 represents what is called a *series wound* machine. The field magnet coils, the armature, and the external conductors are in series with each other, forming a simple circuit. This arrangement has the defect that variations in the external resistance may produce large changes in the current. If the resistance were doubled the current would be halved, supposing the E.M.F.

to remain constant; but the E.M.F. does not remain constant, for as the current through the field magnet coils diminishes the field becomes less intense, and therefore the E.M.F. falls. Accordingly the current becomes less than half what it was. If the current is stopped the field magnets almost entirely lose their magnetism. Consequently there is no difference of potential between the terminals of the machine when the circuit is broken, and in this respect the series wound dynamo differs from a battery. Such machines cannot be used to charge accumulators, for there is always a danger that the E.M.F. of the latter may overpower that of the dynamo, in which case the polarity of the field magnets would be reversed and the accumulators would be discharged instead of charged by the machine.

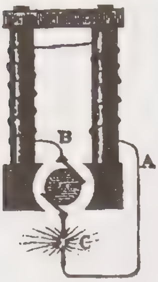


Fig. 609.

A third type is that represented in fig. 610, and is known as the *shunt wound* dynamo. The field magnet coils and the external resistance are in parallel or shunt with each other, instead of in series as in the series wound dynamo. The brushes are connected with the external circuit—for instance, an electroplating bath—and also with the ends of the field magnet coils. These coils are of fine wire, and have a considerable resistance. When the machine is running there will always be a current through the field magnets, whether the external circuit is completed or not. If a break occurs in the external resistance the effect is that a more powerful current passes through the field magnets, which are thus again in readiness to act when the circuit is restored. An increase in the external resistance has but small effect; for if the E.M.F. remained constant the current would only diminish in accordance with Ohm's law, and as a relatively larger proportion of the current now goes through the field magnets, the latter are more strongly excited, and thus the E.M.F. increased; the current is, in fact, lessened in a smaller degree than that in which the resistance is increased. Such machines are used for electroplating and other electrolytic work.

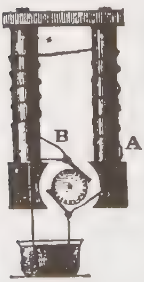


Fig. 610.

The *compound wound* dynamo is represented in fig. 611. It

is a combination of series and shunt machines. Imagine the machine to be series wound to begin with, the field magnet coils consisting of a comparatively small number of turns of thick wire; and then let the brushes be joined to the ends of other field magnet coils of considerable resistance as in the shunt machine.

Dynamos may be compounded either for constant potential or for constant current. Constant potential machines are used for electric lighting where glow-lamps are the source of illumination. The lamps are arranged in parallel as shown in the figure. The difference of potential between the terminals being constant, the current through each lamp, and therefore the light it gives, will be unaltered when other lamps are switched on or off. Constant current dynamos are used for driving arc-lights in series.

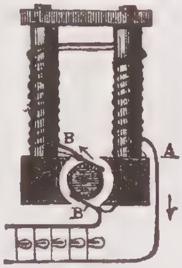


Fig. 611.

556. **Ruhmkorff's coil.**—This is an arrangement for producing induced currents by the action of a voltaic current, the circuit of which is alternately opened and closed in rapid succession. These instruments, known as *inductoriums* or *induction coils*, present considerable variety in their construction, but all consist essentially of a hollow cylinder in which is a bar of soft iron, or bundle of iron wires, with two helices coiled round it, one (the primary) connected with the poles of a battery, the circuit of which is alternately made and broken by a self-acting arrangement, and the other (the secondary) serving for the development of the induced current. By means of these apparatus, physical, chemical, and physiological effects are produced by the aid of three or four Grove's cells, equal and even superior to those obtainable with electric machines and even powerful Leyden batteries.

Of all the forms of induction coils, those constructed by Ruhmkorff in Paris, and by Apps in England, are the most powerful. Fig. 612 is a representation of one, the coil of which is about 14 inches in length. The *primary* wire is of copper, and is about 2 mm. in diameter and 4 or 5 yards in length. It is coiled directly on a cylinder of cardboard, which forms the nucleus of the apparatus, and is enclosed in an insulating cylinder of ebonite. On this is coiled the secondary wire, which is also of copper, and is about $\frac{1}{3}$ mm. in diameter. An important point in connection

with induction coils is the insulation. The wires are not merely insulated by being in the first case covered with silk, but each individual coil is separated from the rest by a layer of melted shellac. The length of the secondary wires varies greatly ; in some of the largest sizes it is as much as two or three hundred miles. With these great lengths the wire is thinner, about ⅛ mm.

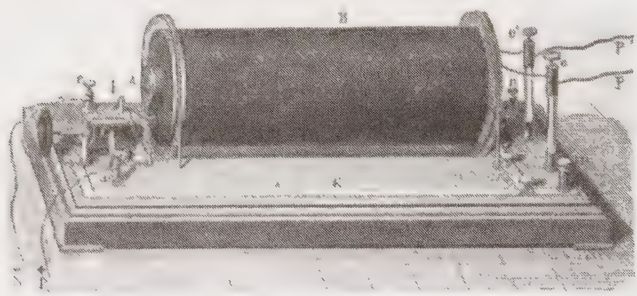


Fig. 612.

The following is the working of the apparatus. The current arriving by the wire, P, at a binding screw, *a*, passes thence into the commutator, C (fig. 612) ; thence by the binding screw, *b*, it enters the primary wire, where it acts inductively on the secondary wire ; having traversed the primary wire it emerges by the wire *s* (fig. 613). Following the direction of the arrows, it will be seen that the current ascends the short pillar, *i*, reaches an oscillating piece of iron, *o*, called the *hammer*, descends by the *anvil*, *h*, and passes into a copper plate, K, which takes it to the commutator, C. It goes thence to the binding screw, *c*, and finally to the negative pole of the battery by the wire N (fig. 612). The current in the primary wire only acts

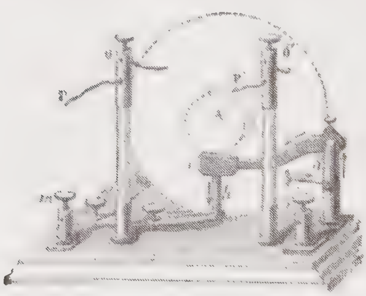


Fig. 613.

inductively on the secondary wire (548) when it starts or stops, and hence it must be constantly interrupted. This is effected by means

of the oscillating hammer, *o*, omitted in fig. 612, but represented on a larger scale in fig. 613. In the centre of the bobbin is a bundle of soft iron wires forming together a cylinder a little longer than the bobbin, and thus projecting at the end as seen at A. When the current passes in the primary wire, this hammer, *o*, is attracted ; but immediately, there being no contact between *o* and *h*, the circuit is broken, the magnetisation ceases, and the hammer falls ; the current again passing, the same series of phenomena recommences, so that the hammer oscillates with great rapidity.

The current thus passes intermittently in the primary wire of the bobbin, and at each break and make of the primary induced currents, alternately direct and inverse, are produced in the secondary wire. This is perfectly insulated, and the E.M.F. acquires such an intensity as to produce very powerful effects. Fizeau increased this intensity by interposing a *condenser* in the primary circuit as a shunt between *i* and *h*. As constructed by Ruhmkorff, for his largest apparatus, it consists of 150 sheets of tinfoil about 18 inches square ; these sheets being joined are coiled on two sides of a sheet of oiled silk, which insulates them, forming thus two armatures ; they are then coiled several times round each other, so that the whole can be placed below the helix in the base of the apparatus. One of these armatures, the positive, is connected with the binding screw *i*, which receives the current on emerging from the bobbin ; and the other, the negative, is connected with the binding screw *m*, which communicates by the plate, K, with the commutator, C, and with the battery.

557. **Effects produced by Ruhmkorff's coil.**—The high potential which the electricity of induction-coils possesses has long been known, and many luminous and calorific effects have been obtained by means of such apparatus. But the improvements which have been introduced into these coils, by careful insulation and attention to the interruption, have enormously increased their power.

Induced currents are produced in the coil at each make and break of contact. But these currents are not equal either in duration or in E.M.F. The direct current, or that on *break*, is of shorter duration but higher E.M.F. ; that of *make*, of longer duration but lower E.M.F. Hence, if the two ends, P and P′, of the fine wire (figs. 612 and 613) are connected, the two currents neutralise each other, as there are two equal and contrary flows of electricity in the wire. If a galvanometer is placed in the circuit,

only a very feeble deflection is produced in the direction of the direct current. This is not the case if the two ends, P and P′, of the wire are separated. As the resistance of the air is then opposed to the passage of the currents, that which has higher E.M.F., that is, the direct one, only passes.

Suppose we obtain, on *break*, a spark an inch long; the E.M.F. or difference of potential between the terminals must be very high—over 50,000 volts. We shall find that in order to obtain a spark on *making* the primary circuit we must bring the terminals almost into contact with each other. Thus, the difference of potential between the terminals when the primary is broken must be enormously greater than that obtained when it is completed.

The effects of the coil, like those of the battery, may be classed under the heads *physiological*, *chemical*, *heating*, *luminous*, *mechanical*; they differ from those of the battery in being enormously more intense.

The *physiological* effects of Ruhmkorff's coil are very powerful; in fact, the shocks are so violent that many experimenters have been suddenly prostrated by them. A rabbit may be killed with an induction current arising from two of Bunsen's cells, and a somewhat larger number of cells would kill a man.

The *heating* effects are also easily observed; it is simply necessary to interpose a very fine wire between the two ends, P and P′, of the secondary wire; this iron wire is immediately melted, and burns with a bright light. The spark of the Ruhmkorff's coil has been used to fire mines in military and mining operations.

The *chemical* effects are very varied, inasmuch as the apparatus produces both the ordinary effects of the current and of electricity at high potential. Thus, according to the shape and distance of the platinum electrodes immersed in water, and to the degree of acidulation of the water, either luminous effects may be produced in water without decomposition, or the water may be decomposed and the mixed gases disengaged at the two poles, or, again, the decomposition may take place, and the mixed gases separate either at a single pole or at both poles.

The *luminous* effects of Ruhmkorff's coil are also very remarkable, and vary according as they take place in air, *in vacuo*, or in very rarefied vapours. In air the coil produces a very bright loud spark, which, with the largest-sized coils, has a length of eighteen inches. *In vacuo* the effects are also remarkable. The experiment is made by connecting the two wires of the coil, P and P′, with the

two rods of the electric egg (fig. 481), used for producing in vacuo the luminous effects of the electric machine. A partial vacuum having been produced, a beautiful luminous trail is produced from one knob to the other, which is virtually constant, and has an intensity similar to that obtained with a powerful electric machine when the plate is turned.

If this light is closely observed, it will be found that if some vapour of turpentine, or wood spirit, or bisulphide of carbon, has been introduced into the globe before exhaustion, instead of being continuous the light consists of a series of alternately dark and bright zones, forming a pile of electric light between the two poles. This phenomenon is known as the *stratification of the electric light*, and is due to the circumstance that the current is discontinuous.

The brilliancy and beauty of the stratification of the electric light are most remarkable when the discharge of the Ruhmkorff's coil takes place in glass tubes containing a highly rarefied vapour or gas. These phenomena, which have been investigated by Masson, Grove, Gassiot, Plücker, etc., are produced by means of sealed glass tubes, first constructed by Geissler, of Bonn, and known as *Geissler's tubes*. These tubes are filled with different gases or vapours, and are then exhausted. At the ends of the tubes two platinum wires are soldered into the glass. (See figures on the right and left in the coloured plate at the beginning of this book.)

When the two platinum wires are connected with a Ruhmkorff's coil, magnificent lustrous striæ, separated by dark bands, are produced all through the tube. These striæ vary in shape, colour, and lustre with the degree of the vacuum, the nature of the gas or vapour, and the dimensions of the tube. The phenomenon has occasionally a still more brilliant aspect from the fluorescence which the electric discharge excites in the glass.

The figure on the right (coloured plate) represents the appearance presented by hydrogen ; in the bulbs the light is a pale lavender blue, in the capillary parts it is red.

In carbonic acid the colour is greenish, and the striæ have not the same shape as in hydrogen ; in nitrogen, as represented in the figure on the left, the light is reddish violet. In chlorine the colour is reddish violet in the wide part of the tube, and in very narrow tubes green.

Mechanical effects.—By means of Ruhmkorff's coil mechanical effects can also be produced, so powerful that, with the largest

apparatus, glass plates two inches thick have been perforated. The result, however, is not obtained by a single discharge, but by several successive discharges.

The experiment is arranged as shown in fig. 614. The two ends of the secondary coil are attached to the binding screws, *a* and *b*; by means of a copper wire, *i*, *a* is connected with the lower part of an apparatus for piercing glass like that already described (fig. 501); the other terminal is attached to the upper conductor by a wire, *d*. This conductor is insulated in a large glass tube, *r*, filled with shellac, which is run in while in a state of fusion. Between the two conductors is the glass to be perforated, V. When this presents too great a resistance, there is danger lest the

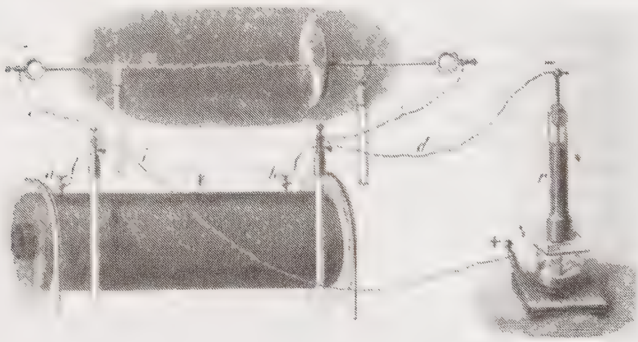


Fig. 614.

spark pass in the coil itself, perforating the insulated layer which separates the wire, and then the coil is destroyed. To prevent this, two wires, *e* and *c*, connect the terminals of the coil with two metal rods, or a rod and a disc, *m* and *n*, whose distance from each other can be regulated. If then the spark cannot penetrate through the glass, it bursts across with a bright spark and a loud report, and the coil is not injured.

558. **Transformers.**—We see from the action of the Ruhmkorff coil that it forms an arrangement by which we may say that electricity of low potential (556) is *transformed* into that of high potential.

If we reverse the function of the parts, we may transform electricity of high potential into that of low; that is, if we connect the

secondary coil of fine wire with a source of electricity of high potential, we shall then have currents of low potential produced by induction in the primary coil.

An important application of this is made in the transmission of electric power, which, as we have seen, is the product of two factors, electromotive force and current, and is expressed by volt-amperes or watts (527). If a given number of watts is to be transmitted to a distance, the transmission may be effected either in the form of a current of great quantity but low electromotive force, or in the form of a weak current but of high electromotive force; thus, if the number of watts to be transmitted is 50,000, this might be as a current of 50 amperes under an electromotive force of 1,000 volts; or it might be as 1,000 amperes with an E.M.F. of 50 volts. Such a current as the latter would, however, require so stout a conductor that the expense would put the transmission out of the question, and accordingly the former mode, requiring a much thinner conductor, would be used. Currents of so high potential as 1,000 volts are, moreover, dangerous, more particularly when in dwellings, and here comes in the utility of the transformers. The current is transmitted through the thin wire, and at the place where it is to be utilised is connected with a transformer the primary and secondary coils of which are so related that the required E.M.F. may be obtained.

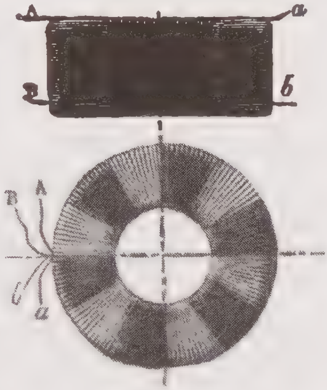


Fig. 615.

Suppose, for example, that electricity at 2,000 volts passes through the transformer, and that the current strength is 5 amperes, so that the power supplied is 10,000 watts or 10 kilowatts. By the transformer this may be converted into electricity at 100 volts (as required for glow-lamps), and assuming there is no loss of power by the conversion, the available current would be 100 amperes, which would feed 200 glow-lamps arranged in parallel if each required ·5 ampere.

In Canada electric power is transmitted from the Shawinigan Falls on the St. Maurice River to Montreal, a distance of 85 miles, at 50,000 volts.

One type of transformer is represented in fig. 615; the core is a bundle of soft iron wire or strips forming a closed magnetic circuit. The two sets of wires, the primary AB and the secondary *ab*, both carefully insulated, are wound on the core either close together or in separate sectors as represented in the figure.

559. **Rotation of induced currents by magnets.**—De la Rive devised an experiment which shows in a most beautiful manner that magnets act on the light in Geissler's tubes in accordance with the laws which govern their action on any other movable conductor conveying a current.

On the iron core of an electromagnet, M (see Frontispiece), is a soft iron rod terminated at the top by an iron plate; this rod, with the exception of the top, *a*, is inserted in a very carefully insulated glass tube. The binding screw, *k*, is in conducting communication with this iron rod. The whole of the upper part of this arrangement is fitted into an electric egg. The brass tubulure, *dd*, which holds the glass tube, is in conducting communication with the binding screw, *h*. By the stopcock at the top the electric egg can be exhausted, and a few drops of alcohol are then introduced.

If now the wires from a Ruhmkorff's coil are connected with the binding screws, *h* and *k*, but without at the same time exciting the electromagnet, a more or less irregular luminous sheaf passes from the plate, *a*, to the ring, *dd*.

But if a voltaic current passes into the electromagnet, the phenomenon is different; instead of starting from different points of the upper surface and the ring, the light is condensed and emits a single luminous arc. Further, and this is the most remarkable part of the experiment, this arc turns slowly round the magnetised cylinder, sometimes in one direction and sometimes in another, according to the direction of the induced current, or the direction of the magnetism evoked in the core. As soon as the magnetisation ceases, the luminous phenomenon reverts to its original appearance.

This experiment is remarkable as having been devised *a priori* by De la Rive to explain, by the influence of terrestrial magnetism, a kind of rotary motion from east to west observed in the aurora borealis. The rotation of the luminous arc in the above experi-

ment can evidently be referred to the rotation of currents by magnets (535).

560. **The Telephone.**—We have already described an instrument in which communications are made through a wire connecting two distinct stations by means of the sound produced by the attractions of an armature against an electromagnet (544). Here, though the sounds are all of the same kind, they may be varied in duration, and, by the suitable combination of short and long sounds, it is possible to produce signals at a distant station which have a perfectly definite meaning.

An instrument has in recent years been invented which is far in advance of this; and whether we look at the simplicity of its principle and of its construction, or at the importance and practical utility of the results already obtained by its means, or again at its promise in the future, it must surely be regarded as one of the

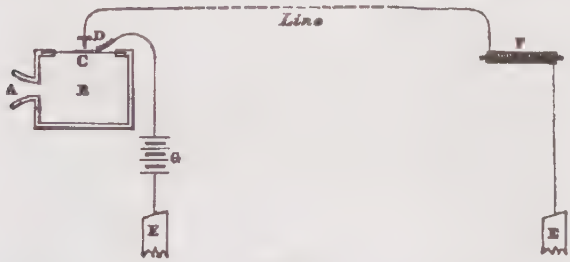


Fig. 616.

most surprising of modern inventions. By its means it is possible not merely to produce sound at a distance, but to produce articulate sounds; to speak audibly, or to send a musical air through a circuit of many miles of ordinary telegraph wire.

Reis in 1862 was the first to make a successful attempt to transmit musical sounds to some distance by means of electricity. The general plan of the apparatus which he used is represented in fig. 616. It consists essentially of a hollow box, B, in one of the sides of which is a mouthpiece, A, while another is closed by a thin membrane. On this membrane is a piece of thin metal foil, C, which is connected with a wire leading to one pole of a battery, G, the other pole of which is put in connection with the earth. Just above the foil, and almost touching it, is adjusted a metal point, D, which is connected by the line wire (540) with one

end of a spiral coil of insulated wire, F, surrounding an iron rod, the other end of which is put to earth (541).

The production of sounds depends on an observation made by Page, that when an iron rod surrounded by a spiral of insulated wire is rapidly magnetised and demagnetised, by the intermittent passage of an electric current, a musical sound is produced which is strengthened by the spiral being placed on a sounding-board.

Now the sounds produced by speaking or singing into the mouthpiece set the membrane in vibration, and alternately open and close the circuit, and the helix with its iron core is rapidly magnetised and demagnetised. Thus F emits a note the pitch of which corresponds to that of the note sounded at A.

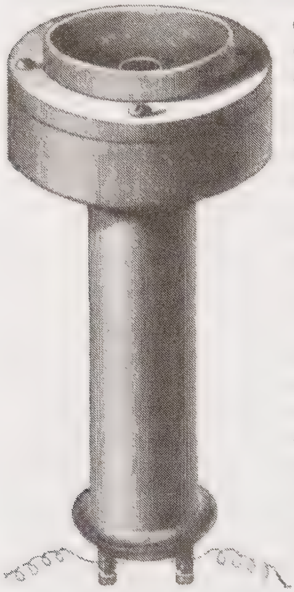


Fig. 617.

The telephone to be described is characterised by far greater simplicity and efficiency, and also by its requiring no battery. It was invented by Professor Graham Bell, of Boston, in 1877. It is represented in something less than half its ordinary size in fig. 617, while fig. 618 gives the details of the construction.

It consists essentially of a steel magnet, M, about 4 inches in length and about half an inch wide, enclosed in a wooden case. Round one end of this magnet is fitted a thin flat coil, BB, of fine insulated copper wire, the ends of which coil pass through longitudinal holes, LL, in the case, and are connected with the binding screws, CC. In front of the magnet, and at a distance which can be regulated by a screw, S, but which is something less than a millimetre, is the essential feature of the instrument, a diaphragm, D, of soft iron, not much thicker than a sheet of stout letter-paper. This diaphragm is screwed down by the mouthpiece, E, which is similar to, though somewhat larger than, that of a stethoscope (181).

The instruments are connected by wires, for one of which the earth may be substituted, as in ordinary telegraphic communication (541). Each instrument can be used either as sender or receiver, though in actual practice it is more convenient for each operator to have two telephones, one of which is held to the ear, while the other is used for speaking into.

The action of the instrument depends on the fact that, whenever the relative positions of a magnet and of a closed coil of wire are altered (549), there is produced within the coil a current or currents of electricity. This may be illustrated by reference to fig. 601. When the magnet is suddenly brought into the coil a current is produced in the coil in a particular direction. There is no current so long as the coil and the magnet are stationary. When, however, the magnet is suddenly withdrawn, a current is produced in

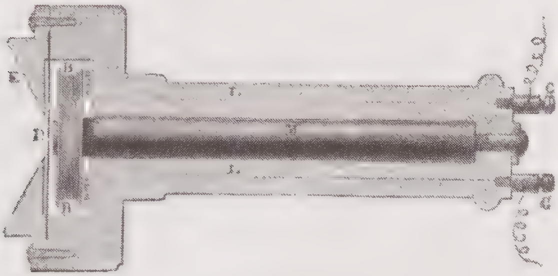


Fig. 618.

the opposite direction. Similar effects are produced if, while the magnet is in the coil, its magnetism is by any means increased or diminished.

Now, in the telephone the magnet and the coil, when once properly adjusted, remain fixed. But the magnet, M, magnetises by induction the soft iron membrane, D, in front of it: that is, converts it into a magnet. When, by the mouthpiece being spoken into, this iron membrane vibrates backwards and forwards, the vibrations give rise to an alteration in the magnetic field inside the coil, BB, the effect of which is that currents are produced in it in alternate directions. These alternating currents, being transmitted through the circuit to the distant coil (the receiver), alternately attract and cease to attract the corresponding diaphragm. They thereby put it in vibration, and when the mouthpiece of the receiver

is held to the ear, these vibrations are perceived as sound, precisely corresponding to that which is transmitted. Hence whatever sound produces the vibration of the diaphragm of the sending instrument is repeated by the second, for its vibrations are exactly reproduced. The telephone is an ***alternate current*** machine.

Although the reproduction of the sound in the receiving instrument is perfect as far as articulation is concerned, it is considerably enfeebled. The sound has something of a metallic character, and appears as if heard through a long length of tubing. It is only perceived by the person using the telephone as a receiver, and he must hold the mouthpiece close to the ear. Hence, in order to attract attention at the distant station, an electric bell worked by a magneto-electric machine, and suitably connected in the circuit, is used as a call. It is difficult to work the instrument on a busy line of telegraphic communication where there are several wires. The electric currents passing in the adjacent wires, and even the vibrations of these wires against the posts on which they rest, produce a continual vibration in the telephone circuit, so that when, under these circumstances, a telephone is held close to the ear, a continuous noise, like the pattering of hail, is heard, which destroys the sound of direct speech. This may, however, be eliminated by having the telephonic circuit of two wires twisted close together, instead of using an earth return ; as they are both at the same distance from the extraneous cause, whatever this may be, its effects are equal and in opposite directions ; they therefore neutralise each other. The limit of power of the telephone has yet to be ascertained. In India it has been found possible to speak audibly through a distance of 500 miles, and even breathing has been heard through a distance of 150 miles. In America conversation has been kept up through a distance of 730 miles ; in France, between Paris and Marseilles, or 500 miles. London is in telephonic communication not only with the large towns in the north of England, but also with Paris and Brussels.

If, while a musical box is being played, the mouthpiece of the telephone is placed upon it, or if the mouthpiece of the instrument is held over an open pianoforte, the music in each case is reproduced at the receiving instrument.

The telephone has been applied, with success, to speak with divers when under water. It has also been used for scientific investigations as a galvanometer ; it reveals the existence of

alternating currents so feeble as to be without action on even the most delicate forms of the ordinary instruments. Experiments made to test its applicability for military purposes are of great promise, and altogether the instrument has, without doubt, a great future before it.

The Ader telephone, which is almost exclusively used in France, is characterised by the circular form of its magnet, A (figs. 619 and 620), which also serves as handle. Another peculiarity is the

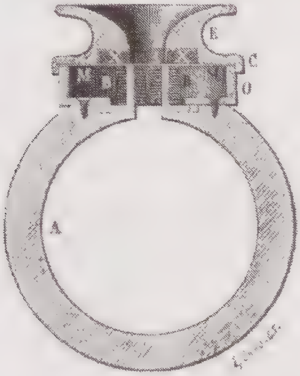


Fig. 619.

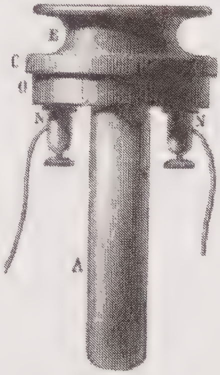


Fig. 620.

Fig. 621.

Fig. 622.

addition of a soft iron ring, XX (fig. 619), called the *sur-exciter*, which acts as armature and increases the magnetic actions. Both poles of the magnet are utilised, and on each a small coil of wire is fixed (figs. 619 and 621). The vibrating plate, M (fig. 619), is placed quite close to and in front of the two poles. E is the mouthpiece, which is of ebonite. Like Bell's telephone, this instrument can be used either f sending or receiving.

The amplitude or extent of the vibrations of the vibrating plate in a telephone is exceedingly small; it is estimated that it does not exceed the twenty-millionth part of an inch.

The current in a telephone was estimated by De la Rue as not exceeding that which would be produced by one Daniell's cell in a circuit of copper wire, 4 mm. in diameter, of a length sufficient to go 290 times round the earth. This current would have to pass 19 years through a water voltameter to produce 1 cc. of detonating gas. This is about 1,000 million times less than the currents in ordinary use. Such currents are, however, sufficient to cause the contraction of a frog's leg (488).

The distance at which conversation can be kept up with the telephone depends less on the kind of telephone than on the

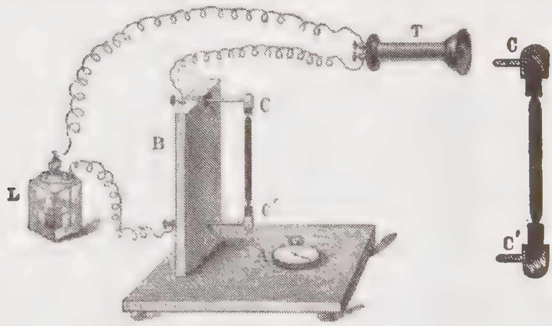


Fig. 623.

nature of the wire. The non-magnetic metal copper is far better than iron, and for long distances the transmission seems proportional to the diameter of the wire.

561. **Microphone.**—This instrument, invented by the late Professor Hughes, derives its name from the fact that it renders sounds audible which to ordinary ears are quite inaudible. Its construction is of great simplicity: fig. 623 represents the form in which it was first made by its inventor. Fixed to a small upright of light wood, B, resting on a base of the same material, A, are two binding screws which terminate in two brass caps, CC′ enclosing pieces of gas graphite. A piece of this substance rests loosely in the cavities in the manner represented on a larger scale in the figure on the side. When this apparatus is connected

up with a battery and a telephone, T, as shown in the figure, the faintest sound produced on the base, the ticking of a watch, the scratching of a pen, or even the creeping of a fly, is distinctly audible in the telephone. The action of the instrument appears to be that when two imperfect conductors, forming part of a voltaic circuit, are in loose contact, any variation in their degree of contact produced by vibration produces a change in the resistance, and this change at once varies the strength of the current in a corresponding way, and these variations again produce exactly corresponding vibrations in the telephone by which they are heard. The effect of the microphone is to draw supplies of energy from the battery, which then appear in the telephone.

To obtain the best results with a particular instrument, the position of the carbon must be carefully adjusted by trial; and, indeed, the form of the instrument itself must be variously modified for the special object in view: in some cases great sensitiveness is required; in others, great range. In order to eliminate as far as possible the effect of accidental vibrations due to the supports, the base should rest on pieces of vulcanised tubing, or on wadding.

The *microphone transmitter*, now in such frequent use, is essentially the same as the above, but its form is somewhat different; it is a sort of frame in which is a thin plate of ebonite, on the back connected up with a cell and a telephone receiver as above shown. When the voice is directed against this plate, it is thereby set in vibration, and these vibrations, varying the strength of the current, are transmitted to the telephone, which then produces the exact words and even the intonation of the speaker.

CHAPTER XIII

THERMOELECTRIC CURRENTS

562. **Thermoelectricity.**—In 1821 Professor Seebeck, in Berlin, found that by heating one of the junctions of a metallic circuit, consisting of two metals soldered together, an electric current was produced. This phenomenon may be shown by means of the apparatus represented in fig. 624, which consists of a plate of copper, *mn*, the ends of which are bent and soldered to a plate of bismuth, *op*. In the interior of the circuit is a magnetic needle, *a*, oscillating on a pivot. When the apparatus is placed in the magnetic meridian, and one of the solderings gently heated, as shown

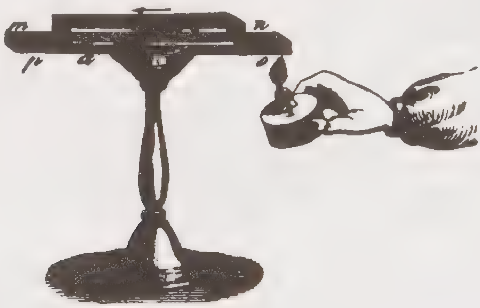


Fig. 624.

in the figure, the needle is deflected in a manner which indicates the passage of a current from *n* to *m* : that is, from the heated to the cool junction in the copper. If, instead of heating the junction, *n*, we cool it by placing upon it cotton-wool moistened with ether, the other junction remaining at the ordinary temperature, a current is produced, but in the opposite direction ; that is to say, from *m* to *n*. In both cases the current is more energetic in proportion as the *difference* in temperature of the solderings is greater.

Seebeck gave the name *thermoelectric* to this current, and the couple which produces it, to distinguish it from the *hydroelectric* or ordinary voltaic current and couple.

563. **Thermoelectric series.**—If small bars of two different metals are soldered together at one end, while the fore ends are connected with a galvanometer, and if the point of junction of the two metals is heated, a current is produced, the direction of which is indicated by the deflection of the needle of the galvanometer (fig. 625). By experimenting in this way with different metals, we may arrange them in a list such that each metal is positive with regard to one of the following, and negative with regard to those that precede; that is, that in heating the soldering the current goes from the positive to the negative metal across the junction, just as if the soldering itself represented the liquid in a hydroelectric element; hence, out of the element, in the connecting wire in the galvanometer for instance, the current goes

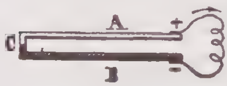


Fig. 625.

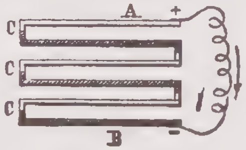


Fig. 626.

from the negative to the positive metal. Thus a couple, bismuth-antimony, heated at the junction would correspond to a couple, zinc-copper, immersed in sulphuric acid. Fig. 626 represents a battery of such elements.

Of all substances, bismuth and selenium produce the greatest electromotive force; but from the expense of this latter element, and on account of its low conducting power, antimony is generally substituted. The antimony is the negative metal but the positive pole, and the bismuth the positive metal but the negative pole, and the current goes from bismuth to antimony across the heated junction.

564. **Nobili's thermoelectric pile.**—Nobili devised a form of thermoelectric battery, or thermopile as it is usually termed, in which there are a large number of elements in a very small space. He joined the couples of bismuth and antimony in such a manner that, after a series of five couples had been made, as represented in fig. 627, the bismuth from *b* was soldered to the antimony, of a second

series, arranged similarly; the last bismuth of this to the antimony of a third, and so on for four vertical series, containing together twenty couples, commencing by antimony, finishing by bismuth. The couples thus arranged are insulated from one another by means of small paper bands covered with varnish, and then enclosed in a copper frame, P (fig. 628), so that only the solderings appear at the two ends of the pile. Two small binding screws, *m* and *n*, insulated by an ivory ring, communicate in the interior, one with the first antimony, representing the positive pole, and the other with the last bismuth, representing the negative pole. To these binding screws are connected the extremities of a galvanometer wire, when the thermoelectric current is to be observed.

Fig. 627.

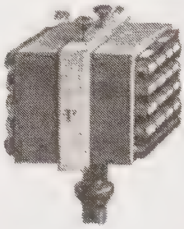


Fig. 628.

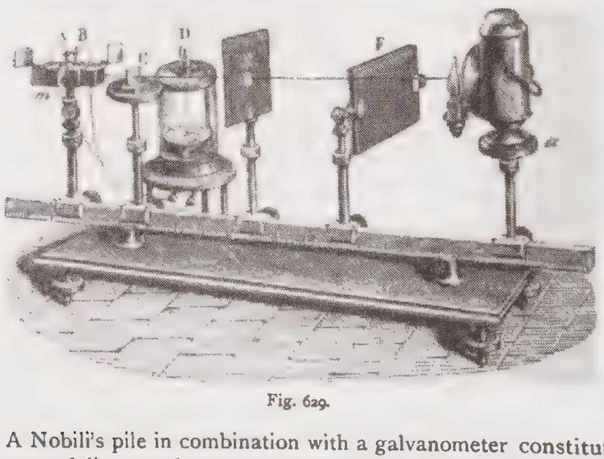


Fig. 629.

A Nobili's pile in combination with a galvanometer constitutes the most delicate and accurate means of measuring temperatures. Such an arrangement was first used by Melloni in his researches on radiant heat (233). The arrangement he used is represented in fig. 629.

On a wooden base, provided with levelling screws, a graduated brass rule, about a yard long, is fixed edgeways. On this rule the various parts composing the apparatus are placed, and their distances can be fixed by means of clamping screws. *a* is a support for a lamp, or other source of heat; F and E are screens; C is a support for the bodies experimented on, and *m* is a thermoelectric battery. Near the apparatus is a galvanometer, D, which has only a comparatively few turns of a tolerably thick (1 mm.) copper wire. The delicacy of this apparatus is so great that the heat of the hand is enough, at a distance of a yard from the pile, to deflect the needle of the galvanometer.

565. **Properties and uses of thermoelectric currents.**—The electromotive force of thermoelectric currents is very low, but they are of great constancy; for their opposite junctions, by means of melting ice and boiling water, can easily be kept at 0° and 100° C. On this account, Ohm used them in the experimental establishment of his law (524). A thermopile of 100 couples of antimony and bismuth with opposite faces at 0° and 100° respectively has an electromotive force nearly equal to that of a Daniell's cell. These thermopiles can produce all the actions of the ordinary battery in kind, though in less degree. By means of a thermopile consisting of 769 elements of iron and German silver, the ends of which differed in temperature by about 10° to 15°, Kohlrausch proved the presence of free positive and negative electricity at the two ends of the open pile respectively.

566. **Thermoelectric needle.**—The thermoelectric couple may be used for determining temperatures in places difficult of access. Two different wires, A and B, are twisted together and connected with a galvanometer G (fig. 630). If then the junction O is exposed to a succession of constant known temperatures, a corresponding deflection of the galvanometer will be observed, from which an empirical table of temperatures can be constructed; hence, if the junction is put in any place its temperature is at once shown by a reading of the galvanometer. By a suitable choice of such couples, considerable ranges of temperature can be observed. Thus, with a platinum and a platinum-rhodium wire, temperatures up to 1200° may be measured with an accuracy of one per cent.—an application of great service in determining the temperature of furnaces, or of the heat involved in chemical reactions in the melting-points of bodies.

Fig. 631 represents the principle of an arrangement devised by

Becquerel for measuring temperatures below 100°. Two identical thermoelectric couples are joined in series in opposition to each other; one of the junctions being placed in the position the temperature of which is to be observed, the other is placed in water,

Fig. 630.

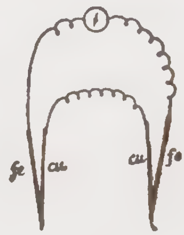


Fig. 631.

the temperature of which is raised or lowered until the needle of the galvanometer is not deflected. The temperatures of the two junctions are then the same, and it is only necessary to read off with a thermometer the temperature of the water.

APPENDIX *of* QUESTIONS

I.—GENERAL PROPERTIES OF MATTER AND UNIVERSAL ATTRACTION

1. What is the difference between a chemical and a physical action? Give some examples of each.

2. What are the three forms in which matter exists?

3. By what properties of the molecules do we account for the existencc of matter in three different forms?

4. Give instances of one and the same body being met with in the three different forms which matter assumes.

5. State and explain what is meant by inertia.

6. Explain the meaning of the terms (*a*) uniform motion; (*b*) uniformly accelerated motion; (*c*) retarded motion; and state how such effects are produced.

7. What effect on the motion of a ship is produced according as the bow or the stern guns are fired?

8. Give an accurate explanation of the process of freeing a carpet from dust by beating it with a stick.

9. Give instances of cases in which it is desired to increase friction; and others in which it is diminished.

10. Give some examples of rolling friction, and some of sliding friction.

11. Why is the bob of a pendulum thinner at the edge than in the middle?

12. How can it be shown that a coin and a feather fall with equal velocity?

13. In rowing, what is the mechanical advantage of feathering the oars?

14. A plummet, the string being held in the hand, is immersed in a current of water, and the string ultimately settles in a somewhat slanting

position. Explain by diagram the nature and action of the forces which determine the position of the string.

15. If while a steamer is steaming along the smoke rises vertically, what conclusion can you draw as to the state of the atmosphere?

16. Give some instances of the practical application of centrifugal force.

17. How is it that a circus rider always leans towards the centre of the circus? If he increases his speed, does he lean more, or less, than he did before?

18. When a man, standing on a horse, which is going at great speed, jumps vertically upwards, what is the direction of the path which his body takes?

19. A ball is thrown vertically upwards in an open railway wagon travelling at high speed. What is the general appearance of its path to a person who sees this as the train passes?

20. When a circus rider jumps through a hoop, in what direction does he spring?

21. In the rotation of the vanes of a windmill, is the velocity of every point on the vane the same? If not, where is it greatest?

22. Explain why and in what circumstances drops of water fly from the surface of a grindstone which is being rapidly turned.

23. Explain why and in what direction drops of water fly from the wheels of a carriage running along a wet road.

24. How is corn separated from chaff in a mill?

25. Account for the fact that it is as easy to play ball on a rapidly moving steamer as it is on land.

26. If at the equator a straight hollow tube were thrust vertically down towards the centre of the earth, and a heavy body were dropped through the centre of this tube, it would soon strike one side. Find which, and give a reason for your reply.

27. If a ball is allowed to drop from the top of a high tower, in what position does it fall in reference to the base of the tower?

28. If two porters, A and B, carry a cask hung to a pole resting on their shoulders, what is the proportion which each porter bears—

(*a*) When the cask is halfway between them;

(*b*) When it is at a distance from A twice that which it is from B;

(*c*) When it is four times as far from B as it is from A?

29. Why is a finger caught in the hinge of a shutting door so severely crushed?

30. Explain the mechanical advantages of steel nippers in drawing nails from wood.

31. Apply the principle of the lever to explain the cracking of a nut by the teeth.

32. In lifting a weight with the hand, show that the lower part of the arm becomes a lever of the third kind.

33. What is the difference between gravitation and gravity?

34. How can you ascertain whether a table is quite horizontal, and whether a wall is quite vertical?

35. Why is it easier for a man to carry a pail of water in each hand than to carry only one?

36. A cart laden with stones may go safely on a road, one side of which is higher than the other; whereas if it carried the same load of hay it might be overturned. Explain this.

37. Why are lamps and candlesticks loaded with weights at the base?

38. How can a body be accurately weighed by means of a balance which is not itself accurate?

39. Why are stepped stairs used in houses instead of a smooth inclined plane?

40. What do we understand by the length of a pendulum in an ordinary clock?

41. How is the ordinary pendulum regulated?

42. What alteration must be made in the length of a seconds pendulum which swings correctly at the sea level, if it is to beat seconds at the top of a hill?

43. Explain the manner in which the oscillations of the pendulum may be applied to determining the figure of the earth.

44. What is the difference between cohesion and chemical affinity? What is the difference between adhesion and chemical affinity?

45. What is the difference between cohesion and adhesion?

46. Give some illustrations of phenomena in which the forces of cohesion, of adhesion, and chemical affinity come respectively into play.

47. Mention some substances which have, in a pre-eminent degree, severally the properties of hardness, of malleability, of elasticity, and of brittleness.

48. Describe the construction and explain the action of the humming-top.

49. Explain the nature of the mechanical operations which a labourer performs in digging earth with a spade and throwing it into a barrow.

50. Why must ships without cargo take ballast on board ?

51. In what sense are we to understand the statement that the spring balance indicates the true weight of a body ?

52. With a horizontal wind a kite ascends. Draw a diagram showing the action of the forces by which it is urged upwards.

53. The head of a hammer is more firmly fixed by striking the end of the handle against the ground. Explain this.

II.—ON LIQUIDS

1. When a stream of water falls into a basin, drops spurt out; of what property of water is this a consequence and a proof?

2. What is the essential difference between liquids and gases?

3. Is a flood-gate which keeps the sea out of a dock exposed to more or less pressure than one which keeps out a lake or river? The depth below the surface of the water is supposed to be the same in each case.

4. Under what conditions does the principle of the equality of pressure of liquids in communicating vessels no longer hold?

5. Illustrate and explain some of the principal phenomena of capillary attraction. What forms do the surfaces of mercury and of water assume in narrow tubes?

6. If one end of a skein of silk is placed in a liquid contained in a vessel, and the other hangs over the side, the vessel is found after some time to be empty. How may this have been brought about?

7. Describe experiments showing the porosity and elasticity of solids, and also of liquids.

8. Describe an experiment which shows that different liquids adhere to solids with varying degrees of force.

9. What are the causes which prevent a jet of water from reaching the height of the water in the reservoir from which it is fed?

10. Why can water-spiders and many other insects run on the surface of the water?

11. When water is poured out of a jug, why is some apt to trickle down below the spout?

12. Why is writing with ink more permanent than with lead-pencil?

13. Describe a simple method of determining the exact volume of any body of irregular shape; a stone, for example.

14. A small cubical box full of water is placed on a large piece of cork which is floated on water. Explain what happens when a hole is made in one side of the box.

15. What metals float on mercury? What metals sink?

16. If a pipe from a gutter fits water-tight into the top of a water-butt, what pressure must be allowed for on the bottom of the butt?

III.—ON GASES

1. What is the main distinction between gases and liquids?

2. Why is atmospheric air chosen as the type of gaseous bodies?

3. How can you prove the existence of an atmosphere?

4. Describe and explain the action of some apparatus which depend on the pressure of the atmosphere.

5. How is the pressure of the atmosphere measured?

6. How can you show that gases have (1) weight, (2) elasticity?

7. Demonstrate experimentally the elasticity of air.

8. What experiment proves that the atmospheric pressure at any given level is transmitted equally in all directions?

9. How can you tell whether the Torricellian vacuum of a barometer is perfectly free from air?

10. Explain how the amount of the atmospheric pressure in pounds is found; and why we are unconscious of its action on our bodies.

11. Is it necessary that a barometer tube be everywhere of the same diameter? Must a thermometer tube have the same calibre throughout? Give reasons for your answers.

12. Explain the principle of the application of the barometer to the measurement of the heights of mountains.

13. Explain the principle of the use of the barometer as an indicator of the state of the weather.

14. Explain the manner in which water is raised in a pipette or in a wine-taster.

15. How do you measure the degree of rarefaction in a receiver attached to an air-pump?

16. Why does a bubble of air liberated at a considerable depth in water gradually increase in size until it reaches the surface?

17. Supposing an air-tight bladder, containing a cubic foot of air, at a depth of about thirty feet in the sea, to be brought to the surface, what would it measure then?

18. If a pound of atmospheric air under the ordinary atmospheric pressure measures 13·07 cubic feet, what will it measure under a pressure of 29·2 inches?

19. What is the main circumstance which limits the depths to which divers can go?

20. If a barometer were carried down in a diving-bell, what would take place? Give a rough quantitative result.

21. Empty and tightly corked soda-water bottles sunk to great depths in the sea, when they are brought up, are often found to contain water, but are still tightly corked. To what may this be due?

22. Explain the use and action of a vent-peg in a beer-barrel.

23. Explain the action of the siphon. Does it act in a vacuum?

24. Explain why a body weighs less in air than in an exhausted receiver.

25. In selling diamonds by weight, is it advantageous to the seller that the barometer should be high or low?

26. Is it advantageous to the buyer that, in buying diamonds, the weights should be of rock crystal or of platinum?

27. How can an aëronaut make his balloon ascend or descend at pleasure?

28. Explain why, when the nozzle and valve-hole of a pair of bellows are stopped, it is difficult to separate the boards.

29. How do you explain the peculiar smell noticed after a shower of rain has fallen on a dusty road?

30. The parts of a whitewashed ceiling immediately under the rafters are lighter in colour than the rest. Account for this.

31. Why is the pressure in an ordinary closed room the same as the pressure in the open air?

32. How would you determine by experiment the volume of air contained in a porous material, such as a brick?

IV.—SOUND

1. Explain what is meant by the wave length of a sound travelling through the air. Give a diagram showing the direction of motion of the air at different parts of the wave.

2. Describe an experiment which proves that sound cannot pass through a vacuum.

3. What are the proofs that water conducts sound?

4. What reasons have you for thinking that solid bodies conduct sound better than gases?

5. Explain why equally loud sounds are heard at very different distances on different days.

6. How is it that the sounds of telegraph wires are heard more distinctly when you put your ear to the telegraph posts?

7. A material, which can only be used in thicknesses of a quarter of an inch, is to be used for the purpose of stopping sound. What experiments could you make with such materials to enable you to select the best?

8. The intensity of a sound varies inversely as the square of the distance from the source. Explain generally why this is so. Does the statement remain true if a speaking trumpet is used to direct the sound?

9. Arrange a few substances in the order in which they transmit sound.

10. Supposing you wish to exclude sound from a room, what principle do you act upon?

11. How is it that you hear a sound originating to windward better than one which arises to leeward of you?

12. Why is the sound of a vibrating tuning-fork stronger when the foot of the fork is placed on a table or on a box?

13. How can the velocity of sound be determined in gases, and how in liquids?

14. Mention some reason for thinking that sounds of high and low pitch travel with the same velocity.

15. A shot is seen to be fired at some distance from the observer; between seeing the flash and hearing the report he counts 8 beats of the pulse (80 in a minute)—what is the distance of the gun?

16. A flash of lightning is observed and the thunder is not heard until fifteen seconds afterwards. Why is this, and what is the distance of the observer from the flash?

17. How distant must a wall be in order that it may echo a word of four syllables?

18. The sound of a gun is echoed from a mountain half a mile off; at what time will the echo reach the person who fires the gun?

19. What experimental evidence would you give that sound can be refracted?

20. A boy holds a stick tightly in a slanting position against some vertical iron railings, which are four inches apart—at what rate must he run so as to produce a note with sixteen vibrations in a second?

21. Describe the construction and explain the action of the safety whistle in steam-engines.

22. Explain the difference between the intensity and the pitch of a sound, and point out the causes which affect the intensity.

23. Explain why sounds are so distinctly heard over a large smooth lake.

24. Describe the siren, and explain how the number of vibrations per second in a given note may be found by means of it.

25. Why is the pitch of women's and boys' voices higher than that of men's?

26. What is resonance? How is it most effectually prevented in enclosed spaces?

27. How would you determine the rate of vibration of a tuning-fork?

28. A person claps his hands in front of a wall, and hears the echo a quarter of a second afterwards. At what distance is he from the wall?

29. Explain how to construct an instrument with strings of the same material and thickness, so that, under the same stretching force, the successive strings may give the consecutive notes of the major scale.

30. Four strings of the same material and length, but of different thicknesses, are stretched on a violin, and tuned so as to give successive fifths; compare the thicknesses of the several strings.

31. Two tuning-forks at the same temperature vibrate at the same rate. One of them is heated. State and explain the effects produced when the forks are now sounded together.

32. A jar containing air, and another containing hydrogen, resound to the same tuning-fork. Are the jars alike? If not, state and explain the difference between them.

33. What would be the general nature of the difference between two tuning-forks of the same dimensions, one of brass and the other of steel?

34. What note makes three times, and what note one-third, as many vibrations as the fundamental note C?

V.—HEAT

1. In what way is the heat of the human body generated and kept up?

2. Describe the general effects of heat upon solids, liquids, and gases.

3. How does heat generally affect the size of bodies? Are there any exceptions to the general rule?

4. Describe the way in which an ordinary mercurial thermometer is made and graduated.

5. How do you proceed to examine whether a thermometer is accurate or not?

6. Compare the advantages and disadvantages of alcohol and water for thermometers.

7. Point out the difficulties which attend the determination of the actual temperature of the air, as distinct from that of surrounding objects, at any time and place, and how errors in the determination may be best avoided.

8. Describe and explain the principle of the gridiron pendulum.

9. Why does a pianoforte get out of tune when brought into a cold room? Is the pitch higher or lower?

10. A belt of ice is placed round the middle of a vertical cylindrical vessel filled with water; one thermometer is placed in the water above the ice-belt and another below it. Describe the changes which take place in the thermometers as the temperature of the water falls from $10°$ to near the freezing-point of water.

11. When a balloon passes from a cloud into sunshine, what danger is likely to ensue if the balloon is not well managed, and what is the cause of it?

12. A certain volume of air, at the temperature of the melting-point of ice, and under the ordinary atmospheric pressure, is contained in a vessel, the pressure of which may be varied. What pressure must be applied in order that, when the temperature of the enclosed air has been raised to that of the boiling-point of water, the volume of the air should remain constant?

13. Why is it possible to seal a piece of platinum wire into a glass tube, but not a piece of brass or iron wire?

14. Illustrate what is understood by the terms *latent heat*, *sensible heat*, *specific heat*. Can you describe some method of determining the specific heat of a body?

15. A copper calorimeter weighs 600 grammes and contains 1 kilogramme of water at 10° C. If 100 grammes of water at 100° are added, calculate the final temperature of the mixture, neglecting external loss of heat, and assuming the specific heat of copper to be 1/10.

16. What is meant by saying that the latent heat of steam on the Centigrade scale of temperature is 537? If Fahrenheit's is the scale employed, what is the value of the latent heat?

17. Give an instance of a great mechanical force exerted by the passage of a liquid from the liquid to a solid state.

18. Mention some substances which are lighter in the solid state than in the liquid state.

19. What metals are suitable for taking sharp casts, and what are not suitable? Give a reason.

20. Compare ether and water, alcohol and linseed oil, camphor and ice, as regards their evaporation.

21. What important part does the great latent heat of water play in the general economy of nature?

22. What is the difference between gases and vapours?

23. Distinguish between a cloud and vapour.

24. Give a reason for the crackling of wood in fires.

25. Explain the singing of a tea-kettle.

26. Mention some substances which pass at once from the solid into the gaseous state.

27. Account for the fact that moist clothes dry upon being exposed to the open air at freezing temperature.

28. Point out, and demonstrate experimentally, how the boiling-point of a liquid may be made to vary.

29. Explain how the height of a place may be found by the temperature at which water boils there. If you had only salt water, would that suffice for this determination?

30. Why cannot meat be properly boiled on the top of high mountains by the ordinary method?

31. What are the several results observed upon continuing the application of heat to a vessel containing ice, at a temperature of 0° C., until the contents of the vessel are raised to 100° C.; and what occurs if the application of heat is continued further?

32. Describe fully the changes which take place when a cubic foot of ice originally at a temperature of −10° C. is continuously heated.

33. When a volatile liquid, such as ether, is dropped on the hand, cold is felt. What is the reason of this?

34. Explain fully the feeling of freshness produced by the watering of streets.

35. In what respect does the manner in which heat is diffused through liquids, and through gases, differ from that in which it is diffused through solids?

36. In what respects are thatched roofs preferable to those of slate or tiles?

37. Explain and give experiments to illustrate the action of the wire gauze surrounding the flame in the safety lamp used in coal mines.

38. When a building is heated by hot water, why is the furnace placed at the bottom? If the density of water at 100° C. is 4 per cent. less than at 18°, find the difference of pressure which produces circulation in a height of fifty feet, if the upflow is at 100° and the downflow at 18°.

39. Explain how the Gulf Stream illustrates the conversion of heat, and state why it moves across the Atlantic in a north-easterly direction.

40. Give some account of the way in which winds are produced.

41. State any consideration, or describe any experiment, which shows that heat is propagated in a vacuum.

42. A square foot and a square inch at different distances from the source of heat receive from this source the same total quantity by radiation. What are their relative distances from the source?

43. How can you prove experimentally that the intensity of radiant heat received by a body diminishes inversely as the square of its distance from the source of heat?

44. How is it that a room with a glass roof, but not heated artificially, becomes much hotter in summer than the outer air?

45. The rays of the sun in passing through a window do not perceptibly heat the panes of glass, but if a glass screen be held in front of the fire it soon becomes warm. Give the reason of this.

46. An earthenware tile, which seen by daylight has a dark pattern on a white ground, is heated to a white heat and viewed as it cools in a dimly lighted room. Explain the appearances it presents as it cools.

47. When the sun's rays have passed through a thick glass plate they will not affect the bulb of an ordinary thermometer, but will act upon a blackened one. Explain this.

48. Why does a thermometer rise higher when the sun shines on a wall near it?

49. Why do grapes ripen better against a wall than in the open? Why better against a dark wall than against a white one?

50. On one side of a plate of cold rock salt is a delicate thermometer; a plate of rock salt and a plate of iron, both at the same high temperature, are successively placed on the other side of the cold rock salt. How is the thermometer affected thereby in each case?

51. Define precisely what is meant by the statement that the boiling-point of water is 100° C.

52. Explain the formation of dew and of hoar frost.

53. On what substances does dew form most freely? Why is none formed under trees?

54. When the steam from a locomotive is seen only slowly to disappear, what conclusion can be drawn as to the state of the atmosphere?

55. State what is understood by the *hygrometric state* of the air; and describe the construction and use of some form of hygrometer.

56. What phenomena are observed when a vessel containing ice or snow is brought into a warm room?

57. Why is dew more abundant on a still, clear night, than on a windy or cloudy night?

58. Explain the following phenomena: (*a*) the moisture on inside walls when a thaw sets in; (*b*) the cloud produced in the receiver of an air-pump when the air is suddenly rarefied; (*c*) the cold experienced on standing near a wall of ice.

59. Define the dew-point. The dew-point is often much higher in summer than in winter, and at the same time the air is drier; how do you account for that? Why is dew seen usually near the ground only, and not so much a few feet above the ground, and on some bodies more than on others?

60. The surface of a pond is observed, under certain atmospheric conditions, to be covered with clouds of mist. Under what circumstances does this occur, and how do you account for the phenomenon?

61. If a stream of air, issuing from a bag which is pressed by a weight, impinges on the face of a thermopile, indications of heat appear; but if the stream issues from an air-gun receiver, into which air had previously been compressed, indications of cold appear: account for these facts on general principles, and give some other illustration of the same principles.

62. Independently of direct measurements, what means of measuring the heights of places do we possess?

63. How is it that an island climate is more moderate than a continental one in the same latitude?

64. What are the chief conditions on which the climate of any place depends?

65. Give some illustrations of the principle that, whenever any of the effects which heat can produce are reversed, heat itself is the result.

66. Explain the principle of the barometer. How is it affected by variations of temperature? Why would a water-barometer be more affected by such variations than a mercurial one?

67. Illustrate the principle that, whenever any of the effects which heat can produce are brought about in any other way, cold is the result.

68. By what means could you produce ice artificially without the aid of a freezing mixture?

69. Describe the physical constitution of a cloud, and explain why it remains suspended in the air. A change of wind from N.E. to S.W., or *vice versâ*, is, in this country, almost always accompanied by rain. Give a rational explanation of this.

70. Give some instances of the production of heat by friction, by percussion, and by pressure.

71. Explain the way in which rain is produced, from the beginning of its formation to the end.

72. Supposing we had no coal and no wood, what sources of heat would still be available to us?

73. What are the two causes which enable us to attain a high speed on railways as compared with horse power on ordinary roads?

74. Why is heavy rain injurious to ripe grapes?

75. The upper surface of a laurel leaf is bright and smooth, the lower surface rough. What effect has this on the temperature?

76. What effect has the opening of a soda-water bottle on the temperature of the liquid?

77. Why is the evaporation from wet grass greater than that from an equal surface of water at the same temperature?

78. If water is kept still it may be raised to above 100° C., even in the open air. If shaken it will burst into ebullition. Explain why only a comparatively small amount is turned into steam.

79. The degree of moisture in the atmosphere affects the velocity of sound; what is the general nature of this action, and what is the physical reason for it?

VI.—LIGHT

1. What analogies and what differences are there between sound and light?

2. Why does a bird at some height in the air cast no shadow on a sunny day?

3. What determines the size of a shadow?

4. A small opaque disc is placed between a large gas flame and a screen; trace the appearance on the screen as the disc is moved from the screen up to the gaslight.

5. Describe and explain the camera obscura.

6. Explain why it is that, whatever be the shape of a small aperture in the wall of a dark room, the image of the sun formed there will be round.

7. Describe a method suitable for comparing the candle power of an oil lamp with that of a gas flame, and explain what measurements are necessary.

8. Suppose five similar candles to burn in a cluster at one end of a rod 10 feet long, and two similar candles at the other end. How far from the cluster of five must a sheet of paper be placed so that the illumination on one of its sides is equal to that on the other?

9. If you can just see to read by moonlight, and also by a candle five yards off, how much brighter is the moon than the candle? Distance of the moon, 240,000 miles.

10. A candle is placed midway between two mirrors inclined at an angle of 45°; draw diagrams showing the paths of rays when an eye looks at each image in succession.

11. Trace the changes in the position of the image formed by a concave spherical mirror, as the object is moved from a great distance up to the surface of the mirror.

12. Account for the fact that a coin placed in water appears higher than it really is, and that shallow lakes appear shallower than they really are.

13. Show by a diagram the manner in which a stick appears bent when placed obliquely in water. Explain the appearance.

14. A coin at the bottom of a basin is invisible to an observer in a certain position, but comes into view when water is poured into the basin;

supposing, instead of water, a liquid with a greater refractive index is poured in, must the height of the liquid be greater or less than that of the water that the observer may see the coin ?

15. Standing in front of either end of an aquarium tank, if you look at the other the back appears nearer ; standing in front of the middle of the tank, the back appears curved. Account for these results.

16. In spearing salmon, what should be the direction of the aim ?

17. Illicit stills have sometimes been discovered by the column of heated air arising from them. How may this be accounted for ?

18. How is the ordinary sight of a person under water affected ? Is he short-sighted, or the reverse ?

19. Trace the course of a ray of light from the visible setting sun to the observer, giving a diagram, and explain the appearance observed.

20. If powdered glass is soaked with an oil of the same refractive index, the individual particles cannot be seen. Explain this.

21. In what circumstances would a colourless mineral be invisible in a liquid ?

22. Account for the transparency of paper which has been soaked in oil.

23. If unpolished colourless precious stones are opaque in consequence of their surfaces being rough, how may they be easily made transparent so that internal flaws can be discovered ?

24. If some black lines are ruled on white paper, and one half covered with a thick piece of plate glass, what effect does an observer perceive when the lines are looked at ?

25. In what direction does an eye under water see an object above the water ?

26. Explain by the aid of a diagram what occurs when light is incident on a glass plate. Explain why a transparent substance, such as glass, is opaque when finely powdered.

27. Describe some experimental method of determining the focal length of a concave spherical mirror.

28. Draw as nearly as you can to scale the path of a ray of light through a prism of refractive index 1·5 and angle 60°, in the case where the angle of incidence is equal to the angle of emergence.

29. How can you determine the focal length of a double convex lens ?

30. Two large thin watchglasses are cemented together so as to form a double convex lens filled with air, and are then immersed in water.

Trace the course of the rays of light falling upon the lens from a luminous point in the axis of the lens and under water.

31. Explain how a convex lens may be used to obtain (1) a real image; (2) a virtual image of an object. Give a sketch to illustrate your answer.

32. Explain by a diagram the formation of multiple images by internal reflection in a thick plate-glass mirror.

33. A convex lens is used to form an image of a candle on a screen. A plate of glass an inch thick is interposed between the lens and the screen. How must the screen be moved to restore the focus? Draw a diagram to explain your answer.

34. What are the practical difficulties which limit the magnifying power of the telescope?

35. A short-sighted person uses an opera-glass which has just been adjusted for long sight. Does he need to alter it? If so, how?

36. You have two achromatic convergent lenses, of 1 inch and 10 inches focal length respectively. How would you combine them to form (*a*) a compound microscope; (*b*) a telescope? Give diagrams showing the action of the lenses in each case.

37. Describe a method by which the velocity of light may be determined.

38. What simple experiment made with a lens would tell you whether the lens were achromatic or not?

39. What appearance does a piece of red sealing-wax present in a room lighted by a pure yellow light?

40. What colours would appear black in a room in which the sun's light is admitted through red glass?

41. If two pieces of the same grey paper are laid, the one upon a black and the other upon a white ground, the former appears lighter. Give an explanation of this.

42. What is short sight, and what long sight? Show the use of spectacles in remedying these defects.

43. Why is short sight usually met with in young and long sight in older persons?

44. Is there any general difference in the structure of the eyes of fishes from those of other animals?

45. Why do the more distant trees in an alley seem to run together?

46. There is a photographic rule that in photographing a building the nearer you are to the building the longer must be the exposure. On what is this rule based?

47. Why does the surface of a table appear brighter when a lamp is surrounded by a semitransparent globe?

48. How is it that an unknown object appears larger in a mist than it really is?

49. Why is moist air more transparent than dry air?

50. Why does ordinary daylight appear dazzling to anyone coming from a dark room?

51. Writing in ink in a particular illumination can be seen in whatever position it is looked at; but writing in pencil only when looked at in certain positions. Explain this.

VII.—MAGNETISM

1. The earth attracts a falling stone; a magnet attracts a piece of soft iron. In what respects do these attractions agree, and in what respects do they differ?

2. In what sense is it true that magnets only attract magnets?

3. One pole of a magnet, made of soft iron and only weakly magnetised, is found to be repelled by the pole of a strong magnet when the latter is some distance away, but to be attracted when the magnets are close together. Explain this.

4. If a piece of hard steel wire (unmagnetised) and a similar piece of soft iron wire are presented to one pole of a magnet, state which you would expect to be attracted with greater force, and give your reason.

5. Five balls of iron hang in a series from the north end of a magnet, but you cannot get a sixth ball to hang: why? The north end of a second magnet is brought directly *over* that of the first; seven balls of iron now cling together: why? You place the second north pole *below* the series of balls; several of them fall away: explain this.

6. Describe a dip needle. How does it behave when the instrument is placed out of the magnetic meridian? How far is the action of the earth on a freely suspended needle similar to that of a powerful magnet?

7. A dip needle is moved completely round the earth, passing through the two poles; describe the changes in its direction of pointing which take place during this operation.

8. Explain why the inclination of a dip needle at any place is less when the needle swings in the magnetic meridian than when the needle swings in any other plane.

9. State how you would magnetise a piece of watch-spring.

10. An iron rod, held vertically and struck with a hammer, becomes magnetised: how do you account for this? How do the position and the striking affect the case? Which end will be the north pole of the rod?

11. How is it that iron tools, such as chisels, &c., are often found to be permanently magnetised?

12. What is meant by the term 'magnetic saturation'?

13. Point out the errors most likely to affect the determination of the bearings of a gallery of a mine by means of a compass.

14. What is the magnetic condition of a bar of soft iron held parallel and near to a bar magnet?

15. A magnet is dipped into a mass of loose iron filings, and when it is withdrawn the poles are surrounded by bunches of filings. Explain this and illustrate the state of the filings by a diagram.

16. How would you place a rod of soft iron for it (1) not to be magnetised, (2) to be magnetised as much as possible along its length by the earth's inductive action?

17. By what experiments could you ascertain whether a sewing-needle is or is not slightly magnetised?

18. Describe and explain the movements of a small compass needle placed in the middle of a horizontal circle round which the N pole of a long vertical magnet is carried. The magnet produces at the centre of the circle a magnetic field less strong than that of the earth.

19. Why is less force required to pull a small iron rod away from the poles of a powerful horseshoe magnet than would be required to pull a thick bar of iron away from the pole of the same magnet?

20. Give your reasons for supposing that there is no such phenomenon as magnetic conduction.

21. State the experiments and the reasoning from which it is inferred that the earth is a magnet.

22. The ends of a bar magnet have the property of attracting iron, but between them there is a part where this property is entirely absent. If a magnet is broken across at the neutral part, what are the properties of the two pieces?

23. Two pieces of magnetised sewing-needles are fastened to corks so as to float horizontally on water. What takes place if the needles are left to themselves, at a distance of a few inches apart, on the surface of the water?

24. A piece of steel is hung from one end of a delicate pair of scales and is accurately counterpoised. It is then magnetised. Does this cause the scale beam to incline in either direction?

25. What effects have a moderate, and what effects an extreme, change of temperature on a magnetised steel bar?

26. Describe the manner in which the magnetic needle is used to trace, in any place, a line due north and south.

27. Why is it that, although a magnetised needle, placed on a cork so as to float horizontally on water, sets north and south, it does not move bodily in either direction?

28. Two sewing-needles, magnetised so that the eyes are north poles, are stuck through cork so that when placed in water they float vertically. What happens when they are brought at a little distance from each other in the water?

29. If two persons, starting from different parts of the earth, were to travel northwards so as always to move in the direction in which the compass needle pointed, towards what region would their paths converge and how would (1) a compass needle, (2) a dip needle, behave there?

VIII.—FRICTIONAL ELECTRICITY

1. How can you prove that whenever one kind of electricity is produced the other is produced at the same time and in the same quantity?

2. What kinds of electricity are produced on each of the following substances when they are rubbed together in pairs—flannel and brass, glass and flannel, guncotton and shellac?

3. How do you prove that there are two kinds of electricity?

4. If you were given a stone, and you were unaware whether it was a conductor or not, explain how you would proceed to determine this point.

5. Why is repulsion a surer test of the electric condition of a body than attraction?

6. Give some instances of the influence of moisture in electric phenomena.

7. What is the best means of depriving a bad conductor of a charge of electricity?

8. In what respect do the forces of magnetism and electricity resemble each other? In what do they differ?

9. Explain the statement that electricity only attracts electrified bodies.

10. An eggshell is placed upon a table, and a stick of sealing-wax rubbed with a flannel is brought near it. As the sealing-wax is moved the egg follows it. Give a full explanation of these results.

11. Sulphur is ground in a porcelain mortar and some of the powder is placed on the cap of a gold-leaf electroscope; the leaves diverge: why?

12. How can heat be converted into electricity?

13. Describe experiments which show that the terms *vitreous* electricity and *resinous* electricity are inappropriate.

14. If you were provided with a body charged with positive electricity, and were required to charge a plate of metal with negative electricity by means of it, how would you proceed?

15. Explain why it is in general easier to impart a charge of electricity to a bar of iron by induction, and to a piece of india-rubber by friction, than *vice versâ*.

16. Given two insulated metal spheres A and B, of which A is charged with positive electricity, and B is uncharged, show how a positive charge

may be communicated to a gold-leaf electroscope by means of A and B without A losing any of its charge.

17. An excited rod of sealing-wax is held about one inch from the wall of a room which may be regarded as a conductor. A proof plane is made to touch the part of the wall nearest the sealing-wax and is then carefully removed to a distance. What is now the electric state of the proof plane as regards charge and potential?

18. How would you prove (1) that the potential is the same at every part on an electrified conductor; (2) that the charge at any part depends upon the shape of the conductor?

19. State the general laws of distribution of electricity on an electrified conductor. Describe the distribution in the case of a hollow tin tube insulated and electrified. How is it modified if you bring your hand near to one end?

20. How can you prove that electricity only resides on the surface of bodies?

21. By what experiment can you prove that a solid sphere of metal cannot be more highly electrified than a hollow shell of the same diameter?

22. A body (A) is brought near a magnetic needle, which is thereby seen to be acted upon. How could you prove whether this action is due to electricity or to magnetism?

23. Describe and explain the action of the electric whirl.

24. Given two similar insulated metal pots and a small charged metal ball suspended by a silk ribbon, how would you charge the pots (1) with equal charges of the same sign, (2) with equal charges of opposite sign?

25. If an electrified body is placed in communication with the earth, or has a sharp point projecting from it, in either case all sign of electricity soon disappears. Explain why this is so by referring to the general laws of distribution of electricity.

26. A bird in a metal cage hung by an insulating cord is unaffected however strongly the cage may be electrified. Show what risk the bird would run on quitting the strongly charged cage.

27. If an insulated tin tube is charged, what difference of electric potential will there be at different parts, both inside and outside the tube?

28. A small ball suspended by a silk thread is placed inside, but not touching, an insulated tin cylinder. The outside of this is then electrified. State and explain the electric condition of the ball when removed from the inside of the cylinder.

29. A sheet of brown paper is dried and smartly rubbed with india-rubber. Explain what takes place when it is placed against the walls of a room.

30. A soap-bubble is blown on the end of an insulated conducting tube; will any change take place if the conductor is electrified?

31. Two equal metal balls are electrified, one five times as strongly as the other. When at a certain distance apart, they are found to repel one another with a force equal to the weight of one grain. If they are brought into contact and then separated to the same distance as before, what force will they exert on each other?

32. On bringing the finger near the knob of a charged gold-leaf electroscope, the divergence of the leaves is seen to diminish. Explain this.

33. How would you screen off from an electroscope the effect of any electrification at a distance?

34. A small piece of gold-leaf, when set free immediately above the knob of a Leyden jar, is seen to hover, neither rising nor falling. Account for this behaviour.

35. A hollow metal cup, the inside of which is coated with sealing-wax, is placed upon the cap of a gold-leaf electroscope. The bottom of the interior of the cup is then rubbed by flannel attached to a non-conducting handle. Describe and explain the behaviour of the leaves of the electroscope (1) while the rubbing is in progress, (2) after the removal of the flannel.

36. Two equal conducting spheres are charged, one with positive and the other with an equal quantity of negative electricity, and are placed a certain distance apart. A third conducting sphere, which is insulated but uncharged, is placed exactly halfway between them. What is (1) the state of electrification, (2) the potential of this last sphere?

37. What is meant when it is said that the earth is the common reservoir of electricity?

38. It is required to compare the insulating power, under water, of two materials, such as gutta-percha and india-rubber. Explain how this may be done.

39. You have several rods of unknown materials. Describe exactly experiments which would enable you to distinguish those which are conductors of electricity from those which are non-conductors.

40. What are the advantages and disadvantages of glass as an insulator in electric apparatus?

41. The bared end of a long insulated wire being given to you, you are

required to determine whether it is charged with electricity, and if so, with what kind of electricity.

42. Explain the use of the prime conductor of a machine. You can draw brighter but not longer sparks by using a large conductor than by using a small one; explain why that is so.

43. A gold-leaf electroscope, the knob of which is connected with the ground by a wire, is placed near the prime conductor of a powerful electric machine in action. Whenever a spark is taken from the machine the leaves suddenly diverge. Explain this.

44. A shallow tea-tray in which are placed some pith balls is placed on a non-conductor, and is then electrified. Explain what takes place when the tray is lifted up by an insulating handle.

45. Could an electric machine be made to act if it had a metal plate instead of a glass plate? If not, why not? If it could, show how.

46. A small insulated electrified sphere is placed at a certain distance from an electroscope. How is the original action on the electroscope affected by separately interposing between it and the sphere (*a*) an ebonite plate, (*b*) an insulated brass plate, (*c*) an uninsulated brass plate?

47. A gold-leaf electroscope, far removed from electrified bodies, is given a weak charge of negative electricity. Explain how its potential varies when a glass rod strongly charged with positive electricity is brought from a distance close up to it.

48. Describe any experiment to illustrate the fact that the spark produced by an electric discharge lasts but a very short time.

49. An insulated electrified ball is brought near the knob of an electroscope, which is then momentarily touched so that the leaves hang vertically. Explain why the leaves diverge when the ball is now moved either nearer to or further from the knob.

50. Describe the mode of charging and discharging a Leyden jar. What circumstances influence the amount of electric charge which such a jar can acquire?

51. A Leyden jar is placed on an insulated stand, and is connected with an electric machine at work; its outer coating is connected with the ground by a wire; state and explain what happens in this wire.

52. A Leyden jar is connected to the positive terminal of an electric machine, the outer coating of the jar being earthed. When charged it is disconnected, and placed on an insulating stand. The inner coating is then put to earth, and the outer coating is touched with the knob of an equal jar held in the hand. Will the second jar be charged, and if so, with what kind of electricity?

53. A Leyden jar is held by its knob while its outer coating is charged by an electric machine. It is then placed on an insulating slab, and the hand, quitting the knob, touches the outer coating, whereupon it receives a spark. Explain this action and state if the jar is discharged.

54. Give an explanation of thunder and lightning, embracing the phenomenon known as the return shock.

55. Would you expect a gold-leaf electroscope to show signs of excitement (1) indoors, (2) out of doors, when there is a thunder-cloud overhead? What sort of effects would you expect in such a case, and how caused?

56. Describe some method of collecting and examining the electricity of the atmosphere.

57. What is a lightning-conductor, and in what way does it act? Suppose you are required to extemporise one for a detached house, give a detailed account of the manner in which you would proceed.

58. If a lightning-conductor on a building be carried near a part of the roof covered with lead, why is it desirable that the lead should be connected with the conductor?

59. Account for the fact that we may have lightning discharges without thunder.

60. If a tall iron rod projecting above the roof of a house is not connected with the ground, but passes near an iron pipe which is so connected, sparks are sometimes seen to pass between the rod and the pipe, even when there is no lightning. Explain this.

IX.—VOLTAIC ELECTRICITY

1. A plate of pure zinc is partially immersed in dilute sulphuric acid: what is its electric state? A plate of copper is also partially immersed in the same liquid: what is its state? The plates are now connected outside the liquid by a wire. State and explain fully what ensues.

2. What are the conditions for the production of a voltaic current? Mention some different arrangements in which these conditions are fulfilled.

3. Mention some of the properties of a wire conveying an electric current. If you were asked to show that, when the two coatings of a charged Leyden jar are connected by a wire, a current of the same nature as that produced by a voltaic cell passes through the wire, how would you proceed?

4. What is meant by polarisation in a galvanic cell? Mention some cell in which there is no polarisation, and explain the reason of its absence.

5. State whether local action or polarisation takes place in (1) a Daniell cell, (2) a Leclanché cell, giving reasons for your statements.

6. What are the chief points of difference between statical and dynamical electricity?

7. A wire traversed by an electric current is placed over and then under a magnetic needle. Describe the effects that are thereby produced.

8. By what means would you ascertain the direction of a current of electricity in a wire the ends of which are hidden from you?

9. The poles of a galvanic cell are connected to the terminals of an astatic galvanometer, and the needles are in consequence deflected through a large angle. When one of the needles of the astatic combination is removed, other things remaining the same, the deflection is small. Explain this.

10. Give two examples of the chemical action of an electric current, and two others of the magnetic action of the same current.

11. A small magnetic needle is feebly magnetised: it is desired to remagnetise it in such a manner that its original polarity is reversed. Describe how you would proceed to do this by means of a voltaic current.

12. The ends of a brass rod on which a steel ring has been slipped are joined to the poles of a voltaic battery. Is the steel ring magnetised by

the passage of the current through the rod? How would you test whether it is or not?

13. You are required to describe distinctly how you would obtain (*a*) a current of frictional electricity; (*b*) a current of voltaic electricity; (*c*) one of thermoelectricity; (*d*) an induced current, by means of a permanent magnet.

14. Given two cells of different electromotive forces, a galvanometer and wires, how would you find out which of the cells has the higher E.M.F.?

15. A current passing through a long wire is so weak that, when the wire is stretched over and parallel to a suspended magnetic needle, the needle is not perceptibly affected. Describe and explain an arrangement which would enable you to obtain a movement of the needle by the action of the current.

16. Describe an arrangement for making a ring traversed by a current float on water. In what way will it set if left to itself? State what takes place according as one or the other pole of a magnet is presented to it.

17. How would you compare two wires as regards their power of conducting electricity?

18. How can you prove experimentally that in a closed voltaic circuit the strength of the current is everywhere the same?

19. A bar of copper weighing one pound is drawn into wire of a certain length; two pounds of the same kind of copper are drawn into wire of four times the length. What is the ratio of the total resistances of the two wires?

20. The poles of a cell are joined by a wire 84 feet in length; after the circuit is opened one third of the wire is bent upon itself, so that the two parts are in contact; and the circuit is again closed by the wire thus modified. What is the ratio of the external resistances in the two cases?

21. What would be the relative resistances of two wires of the same material, one of which was three times as long but only half as heavy as the other?

22. If at a place where the declination is easterly there is an earth current from east to west, what effect will it have on a compass needle?

23. Two large insulated flat brass plates are set facing each other and very near together. A wire from one of them is joined to the zinc end of a battery of a great many cells; and a wire from the other plate is joined to the other end (copper or platinum) of the battery. Without touching

either the wires or plates with conductors, the wires are removed from the plates, and the plates then moved to a distance from each other. What will now be the electric condition of each plate?

24. Two delicate astatic galvanometers are connected by a long length of wire so that their coils form one continuous circuit. Explain what happens when the magnet of one of them is moved.

25. Copper and platinum wires of the same length and section are wound on two glass tubes, the coils being in every respect alike. If they are connected together to a battery so that the same current passes through them, explain how they will differ from each other in respect of (1) their action on a compass needle; (2) their rise of temperature.

26. The poles of a voltaic battery are joined to the ends of a chain composed of alternate links of copper and iron of the same thickness. It is noticed that the iron links become hotter than the copper links. Explain this.

27. Describe the general construction of an incandescent electric lamp, and explain why a high temperature is produced only within the lamp.

28. A rod of carbon, thick at one end and tapering towards the other end, is connected by copper wires to the poles of a battery. If the battery is powerful, what appearance will the carbon present?

29. You are required to coil a wire, and then to suspend it so that the axis of the coil, when a voltaic current is sent through it, shall set like a magnetic needle in the magnetic meridian. Show by a sketch how this is to be done.

30. Describe an experiment which proves that electric currents flowing in the same direction attract each other, while currents flowing in opposite directions repel each other.

31. Describe some experiment to prove that, when the terminals of a voltaic battery are connected by a wire, the liquid in the battery itself is traversed by an electric current.

32. A strip of gold leaf attached to two metal conductors hangs somewhat loosely in a vertical position between the two poles of a horseshoe magnet. When a current of electricity is passed through the gold leaf, what takes place?

33. A compass needle is placed at the centre of a vertical ring of wire. If the plane of the ring lies east and west, the needle is not necessarily deflected when a current of electricity is sent round the ring; if, however, the plane of the ring is north or south, the needle is violently deflected when the current passes. Explain this.

34. A metal ring through which a current circulates can move horizontally, its plane remaining vertical. Describe and explain what happens when one pole or the other of a bar magnet is presented to the ring.

35. Describe and explain how the magnetic effects of a coil of wire through which a current is passed is affected by introducing into the coil a rod of soft iron of the same length as the coil.

36. What are the essentials for establishing electric telegraphic communication between two places?

37. What would be the general nature of the effects produced by a complete break in a telegraph line on the signals of the sending and on those of the receiving station? What, in like manner, would be the effect of a leak?

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